THE STRATIGRAPHY, SEDIMENTOLOGY AND PETROGRAPHY OF THE JURASSIC-EARLY CRETACEOUS CLASTIC WEDGE IN WESTERN ALBERTA

By

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Submitted to the Faculty of Graduate Studies, University of Manitoba in partial fufillment of the requirements for a doctoral degree in Science

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ABSTRACT

During the Late Mesozoic, the Western Canadian Sedimentary Basin evolved from a simple passive margin to a complex foreland basin. This thesis is an integrated outcrop and subsurface study of the stratigraphy, sedimentology, petrography and reservoir and source rock potential of the strata which record this transition in western Alberta.

The Early to Late Jurassic Fernie Formation is a thin, condensed sequence of marine shales, cherts, carbonates and highly quartzose (craton-derived) sandstones. The overlying Late Jurassic Cretaceous Kootenay and Nikanassin strata comprise a westward-thickening wedge of quartz and chert-rich (Cordilleran-derived) sandstones which are truncated by the pre-Cadomin unconformity. This unconformity records a major isostatic uplift of the orogen, and associated foreland basin. This uplift was probably initiated by collision-related crustal thickening and accentuated as the thrust sheet load was bevelled by erosion. The overlying Early Cretaceous Blairmore, Mannville and Luscar strata record another episode of basin subsidence resulting from additional thrusting in the foreland fold/thrust belt. The basal Cadomin, Gladstone, and equivalent Lower Ellerslie strata are Neocomian to Aptian in age. This interval contains quartz and chert-rich sandstones which were deposited by northwest-flowing river systems which traversed an aggrading alluvial plain. The Upper Ellerslie, Glauconite and equivalent Moosebar Formations are Aptian to Late Albian in age and comprise a northwestward-thickening wedge of brackish-marine mudstones and sandstones which were deposited during

the episodic advance, and retreat, of the boreal Clearwater Sea into western Alberta. The overlying Beaver Mines and Gates Formations are Middle Albian in age. These strata record a major influx of coarse detritus into the basin from a volcanic source terrane in the southern Cordillera.

The chert and quartz-rich sandstones at the base and middle of the Blairmore-Mannville interval comprise good hydrocarbon reservoirs in western Alberta which typically retain fair-good primary porosity. The highly-quartzose Jurassic sandstones are typically tightly cemented with quartz overgrowths whereas the feldspathic sandstones in the upper part of the section are plugged with clay-carbonate cement. The Jurassic to Early Cretaceous shales are mature in the western Plains, overmature in the Foothills and are moderately rich in type II and type III organic matter.

Acknowledgements

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Most importantly, I want to thank my wife Gisele, my three great kids Matthew, Louis & Danielle, and my parents for four years of unqualified support and encouragement. I couldn't have done it without you.

TABLE OF CONTENTS

PAGE

PAGE

Appendices

LIST OF FIGURES

PAGE

CHAPTER 1 INTRODUCTION

In western Alberta, Jurassic-Early Cretaceous clastic sedimentary rocks record the transition of the Western Canadian Sedimentary Basin from a simple passive margin to a complex foreland basin. Massive coal reserves are contained in the Kootenay-Luscar strata in the Foothills and equivalent (Mannville) strata in the western Plains host important reserves of conventional and heavy oil. Despite their tectonic and economic significance, however, no comprehensive regional syntheses have been published which document the detailed depositional facies and history, paleogeography and reservoir and source rock potential of these strata. To address these problems, a study area was selected in western Alberta and a large number of drill cores and outcrop exposures of these strata were studied in detail.

(A) OBJECTIVES

The objectives of this study were:

i) to collect, compile and interpret outcrop and subsurface (drill core and geophysical log) data for the purposes of refining nomenclature schemes and resolving correlation problems within this interval. Existing nomenclature schemes are based on simplistic layer-cake depositional models which are not applicable in complex successions such as the Jurassic-Early Cretaceous wedge of Alberta which is reported to contain interbedded marine and non-marine sequences, locally dissected by deeply incised channels (Hopkins 1981; Jackson 1984). Micropaleontology, major element chemistry and light mineral petrographic data were employed to support the revised stratigraphic correlations.

ii) to document and interpret the depositional facies and sequences present in different parts of the basin, and to relate these facies to depositional history. The paleogeography of the basin was established by integrating a series of isopach maps, which established the geometry of the various lithostratigraphic units, with the facies, microfossil and paleocurrent data collected.

iii) to evaluate the provenance of the clastic detritus (i.e. discrimination of craton versus Cordilleran sources) and to provide insight into the tectonic history of the Cordillera by studying the framework composition and major element chemistry of representative samples of the Jurassic and Early Cretaceous sandstones. The diagenetic history and cementation pattern of these sandstones was also studied using light mineral petrography and XRD techniques.

iv) to document the source rock potential of the shales deposited during the different stages of basin evolution and to estimate the total volume of hydrocarbons which might have been generated by these strata.

(B) STUDY AREA AND DATA BASE

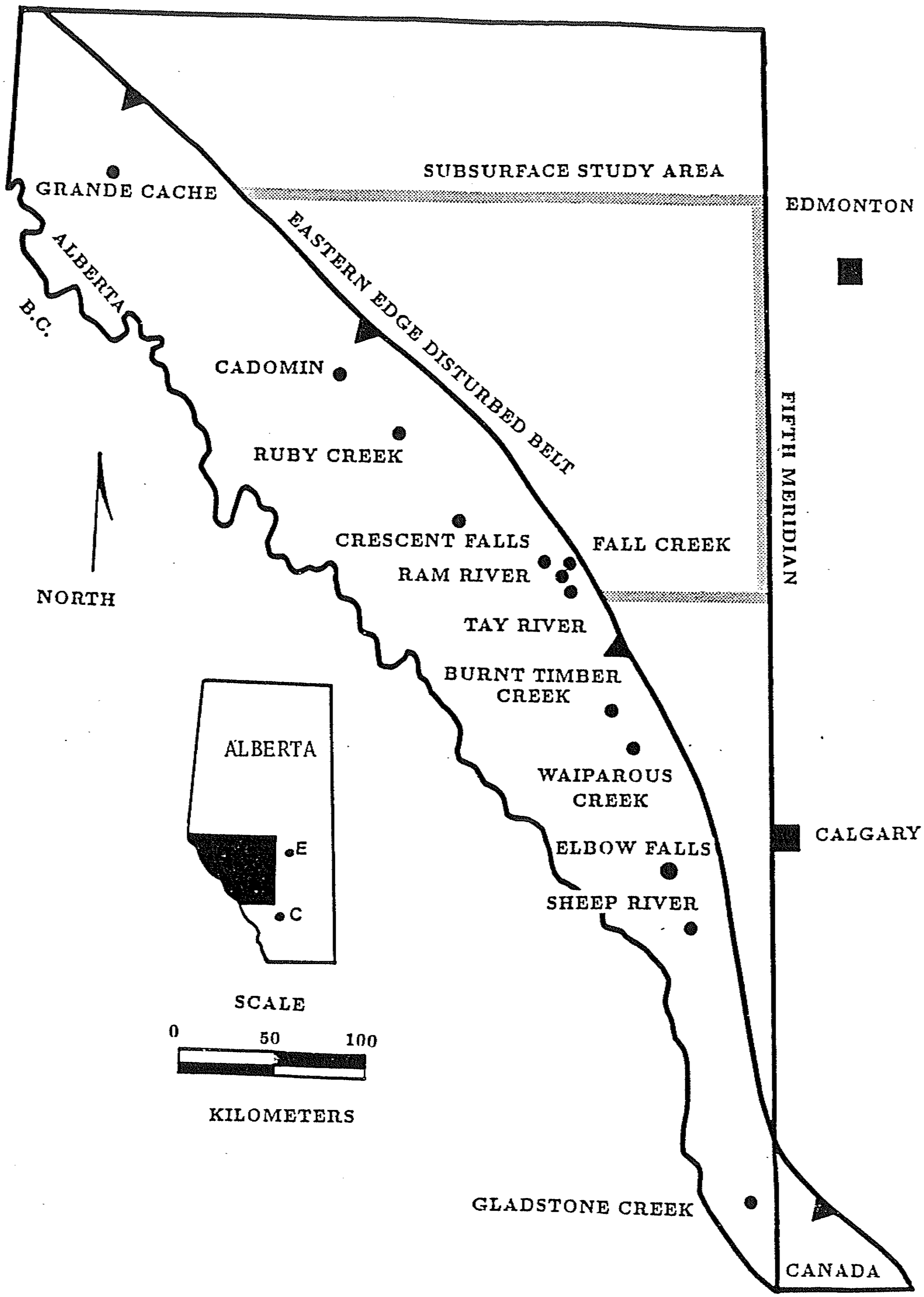
The study area selected straddles the boundary of the Rocky Mountain

Foothills and the Plains of west-central Alberta (Fig. 1). Direct comparison of outcrop exposures and drill cores of correlative strata is possible in this area because undisturbed strata which have been buried to depths of several kilometers in the Plains in the eastern portion of the study area have been uplifted, and exposed at surface, in the fold/thrust belt in the western portion of the study area. The twelve outcrop sections measured in this study are located in the west central Foothills and Main Ranges of the Rocky Mountains between Sheep River and Grande Cache, Alberta (Fig. 1). The location and access instructions for each of these sections is listed in Appendix 1. The subsurface data consisted of 200 drill cores and 1300 geophysical well logs from wells in the area TWP 36-56, R1W5-R25W5 and the location of all cores measured is listed in Appendix 2 and plotted in Figure 2. This area totals approximately 20,000 km^2 (350 townships) and the sample density for the entire area is approximately 1 core per 100 km^2. In the central part of the study area (TWP 40-50, R1W5-R25W5), geophysical logs from every non-confidential borehole were incorporated into the study whereas in the areas to the north and south, only wells which cored all or part of the Jurassic or Early Cretaceous strata were included.

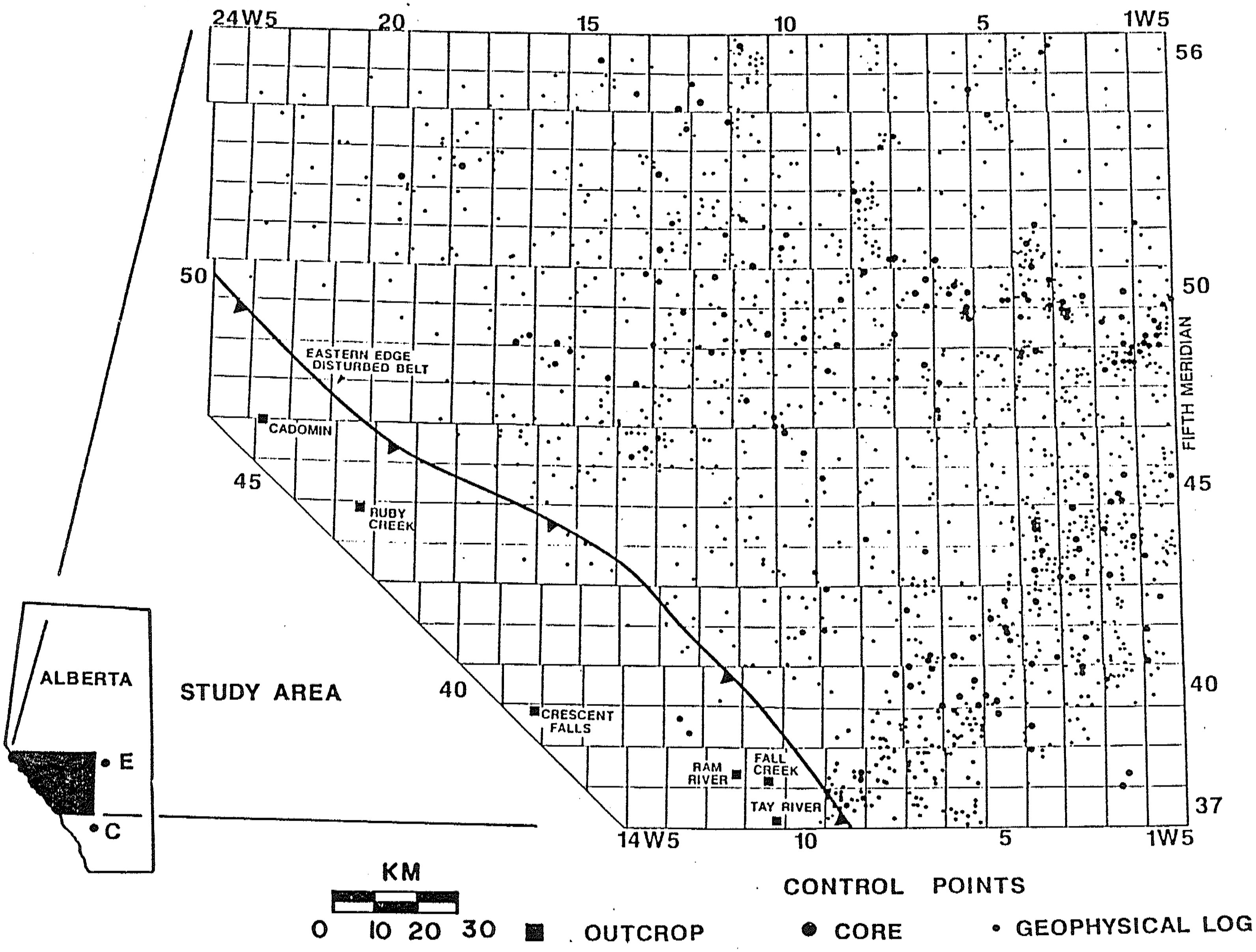
(C) METHODOLOGY

The cores and outcrops were measured in detail and described in terms of color, grain size, abundance and type of physical and organic sedimentary structures, and the nature of the contacts between the various depositional facies. A detailed description of all cores is contained in Appendix 3A and the outcrop sections are plotted and correlated in Appendix 3B.

For the subsurface part of the study, a series of stratigraphic cross sections were constructed (1 cross-section per township) to establish regional



(1) Map showing location of outcrops & subsurface study area. Edge of disturbed belt from Jackson (1984).



(2) Detailed map of subsurface study area showing location of cores and geophysical logs used in this study.

correlations across the study area. Core data was integrated with these sections to resolve some of the correlation problems and the Jurassic- Early Cretaceous strata were subdivided into a series of "slices", based on their relationship to prominent contacts such as the Jurassic-Cretaceous unconformity, major coal horizons and a series of distinctive shale beds which appear to mark major transgressive (flooding) events. Six representative subsurface cross sections are included in the thesis and these were integrated with isopach and net sand maps(constructed using well log and core data) to establish the geometry of the various lithostratigraphic units.

Representative samples of sandstones from each stratigraphic unit were analyzed using a variety of techniques to document and interpret stratigraphic variations in framework composition, provenance, cementation patterns and reservoir potential. Thin sections of one hundred sandstones were point counted and fifteen sandstone samples were also analyzed for major element composition, using XRD and XRF techniques.

To establish the source rock characteristics of the Jurassic- Early Cretaceous succession, 95 shale samples were analyzed using RockEval instrumentation. To determine the age, and depositional environment represented by the prominent shale markers, 37 samples were selected for micropaleontologic analysis (forามininfera, dinoflagellate, and pollen counts). Appendix 6 lists the location, depth and stratigraphic interval and interpreted age and environment represented by each of these shale samples .

(D) THESIS FORMAT

A discussion of the objectives and methodology employed in this study is presented in Chapter 1 and a stratigraphic and structural overview of the

Western Canadian Sedimentary Basin is outlined in Chapter 2. The stratigraphic nomenclature schemes employed in various parts of the basin are discussed in Chapter 3 and a brief review of previous sedimentological investigations is outlined in Chapter 4. Chapter 5 summarizes the descriptions and interpretations proposed for each depositional facies and Chapter 6 focuses on the recognition and correlation of the various facies sequences across the study area. Chapter 7 is concerned with the stratigraphic variation in sandstone composition and relates these changes in framework composition and major element chemistry to changing source terrane and dispersal patterns. Chapter 8 is a review of the diagenesis and reservoir potential of these sandstones and Chapter 9 relates the limited amount of paleocurrent data collected in this study with paleogeography of the basin. Chapter 10 is a discussion of the source rock characteristics of the Jurassic-Early Cretaceous shales in the study area which closes with a numerical estimate of the volume of hydrocarbons which could have been generated by these strata. Chapter 11 introduces a general depositional and tectonic model to explain the age, distribution and characteristics of the Jurassic-Early Cretaceous clastic wedge in the Alberta Basin and Chapter 12 summarizes the conclusions of this thesis dissertation.

CHAPTER 2 OVERVIEW OF THE WESTERN CANADIAN SEDIMENTARY BASIN

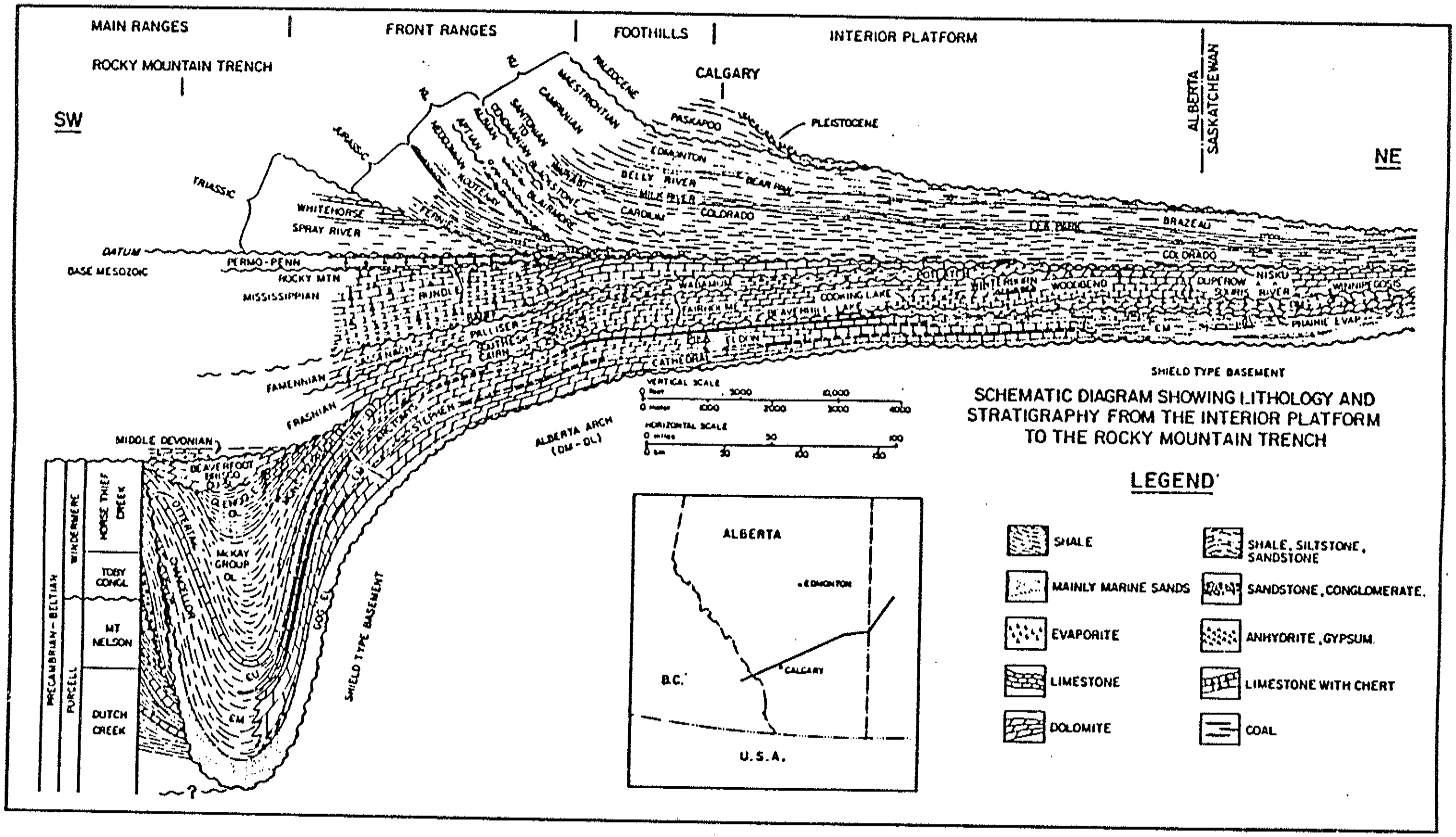
The Western Canadian Sedimentary Basin is a westward-thickening wedge of clastic and carbonate strata of Proterozoic-Phanerozoic age which onlaps an eroded Precambrian (Archean-Helikian) crystalline basement complex. A schematic section across this basin is shown in Fig. 3. The following summary of the stratigraphic and tectonic history of the basin is gleaned from comprehensive works by McCrossan and Glaister (1964), Monger et al. (1982), and Lambert and Chamberlin (1988).

(A) TECTONIC HISTORY

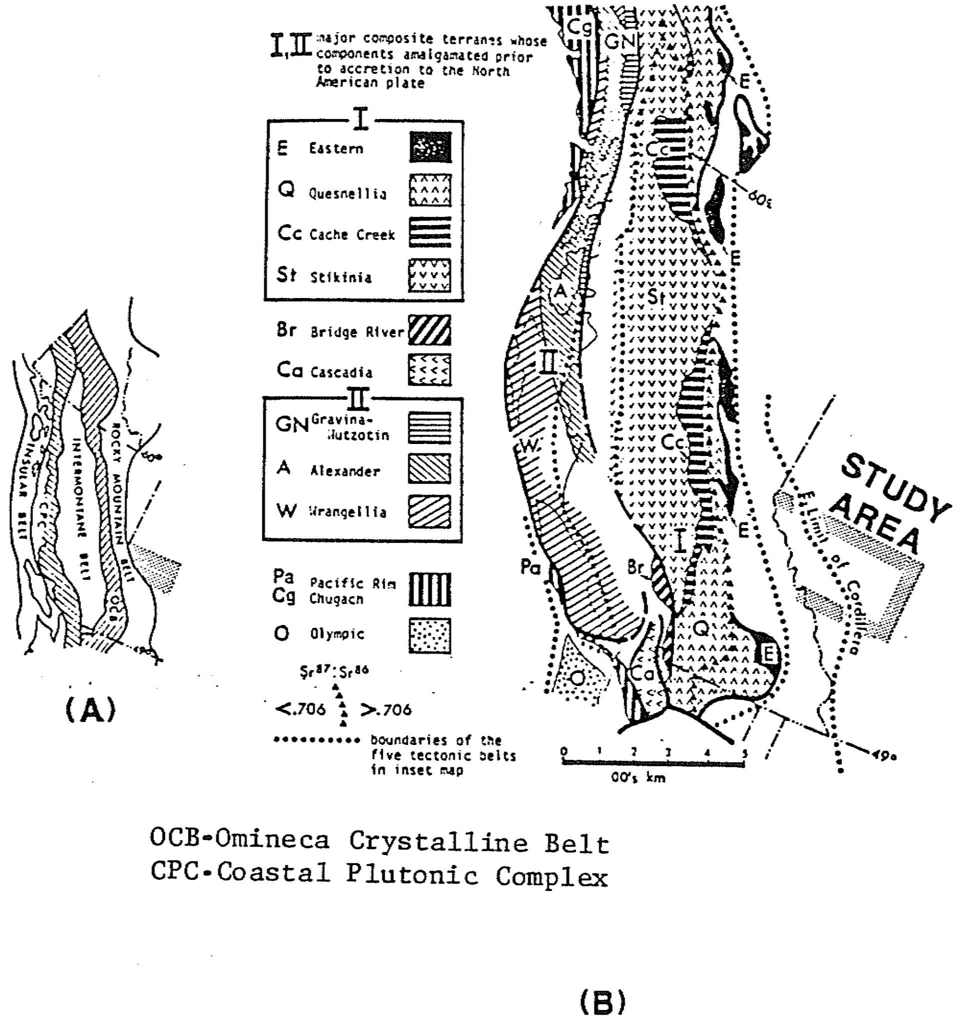
Two distinct evolutionary stages are recognized in the Western Canadian Sedimentary Basin. During the Middle Proterozoic to Early Jurassic, western North America was a relatively stable passive margin in which shallow marine carbonates and highly quartzose (craton-derived) sandstones were deposited. Along the extreme westward margin of the craton, kilometer-thick shale sequences were deposited along the prograding shelf, slope and rise which flanked the craton. Most of the strata exposed in the Front and Main Ranges of the Rocky Mountains were deposited during this passive margin stage.

In the Late Mesozoic Era, the western margin of North America evolved into an active (convergent) plate margin. Two radically different tectonic models have emerged to explain the complex tectonic history of the Cordillera during this time.

The model proposed by Monger et al. (1982), and Price and Carmichael (1986) suggested that the complex structural geology in the Cordillera is the record of two separate collision events along this active margin as exotic terranes were accreted to the craton. The first collision occurred during the Late Jurassic to Early Cretaceous, after the oceanic plate underlying the ancestral



(3) Schematic east-west cross section traversing the Western Canadian Sedimentary Basin (after Gordy et al. 1972).



OCB-Omineca Crystalline Belt
CPC-Coastal Plutonic Complex

(4) Tectonic map of southern Canadian Cordillera showing location of the study area relative to A) the major geological provinces in the Cordillera and B) the allochthonous terranes in the Cordillera (from Monger et al. 1982).

"Anvil Ocean" had been consumed below a westward-dipping subduction zone. This resulted in the collision of a composite exotic terrane, composed of the Stikinia, Cache Creek, Quesnellia, and Eastern Blocks, against the western margin of the craton (Fig.4). The episode of magmatism, metamorphism and uplift which accompanied this collision is termed the Columbian Orogeny (Monger et al. 1982). In this model, a second collision event occurred during the Late Cretaceous as a second composite terrane was accreted to the continent and the resulting tectonism and magmatism which accompanied this was termed the Laramide orogeny. This second orogeny ended with a major episode of strike-slip faulting (Monger et al. 1982).

Lambert and Chamberlin (1988) present an alternative interpretation of the structure of the Rocky Mountains which invokes a single collision of the North American Craton with a composite allochthonous terrane which they termed Cordilleria. They cite paleomagnetic and paleontologic data which indicates that the smaller terranes comprising Cordilleria were initially formed at least 2000 kilometers south of their present position. Monger et al. (1982) suggested that this displacement occurred during the Late Cretaceous-Tertiary strike-slip faulting although it was later recognized that faults with this scale of displacement could not be found not in the southern Cordillera (Price and Carmichael 1986). Lambert and Chamberlin (1988) suggested that the Omineca Crystalline Belt (Fig.4) formed during the Middle Jurassic, during which time it was part of a separate allochthonous terrane located far south of its present position. They suggest that most Jurassic to Early Cretaceous magmatism and metamorphism which affected this allochthonous terrane occurred prior to its accretion to the North American Craton. In this model, most of the relative displacement between Cordilleria and the craton (indicated by the paleomagnetic data) was taken up by oblique subduction below a west-dipping subduction zone. They also suggest that maximum displacement along the transcurrent fault systems (e.g., Tintina-Rocky Mountain Trench Faults) was found in the northern Cordillera where Cordilleria had first collided with the craton during the Albian. This model is difficult to reconcile with sedimentological evidence that the basin was receiving westerly-derived sediment prior to the Albian (Stott 1984).

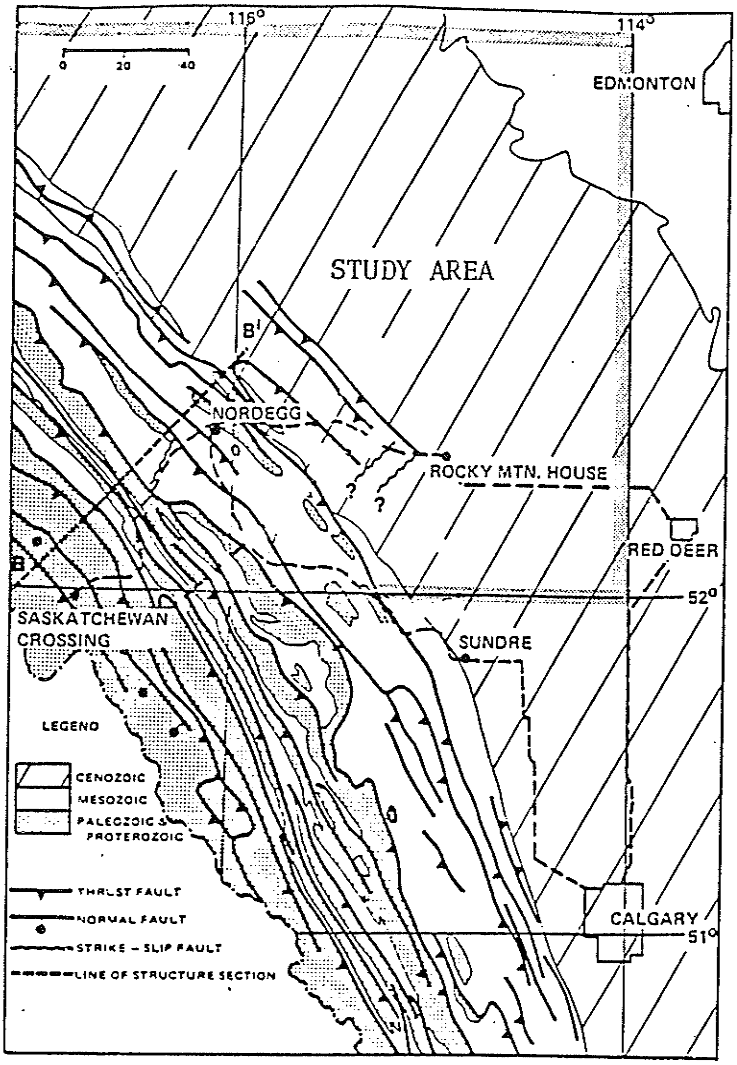
In summary, several problems exist with both models currently invoked to explain the tectonic history of the Cordillera and these problems, and an alternative model, will be discussed in more detail in Chapter 11.

(B) STRUCTURAL SETTING

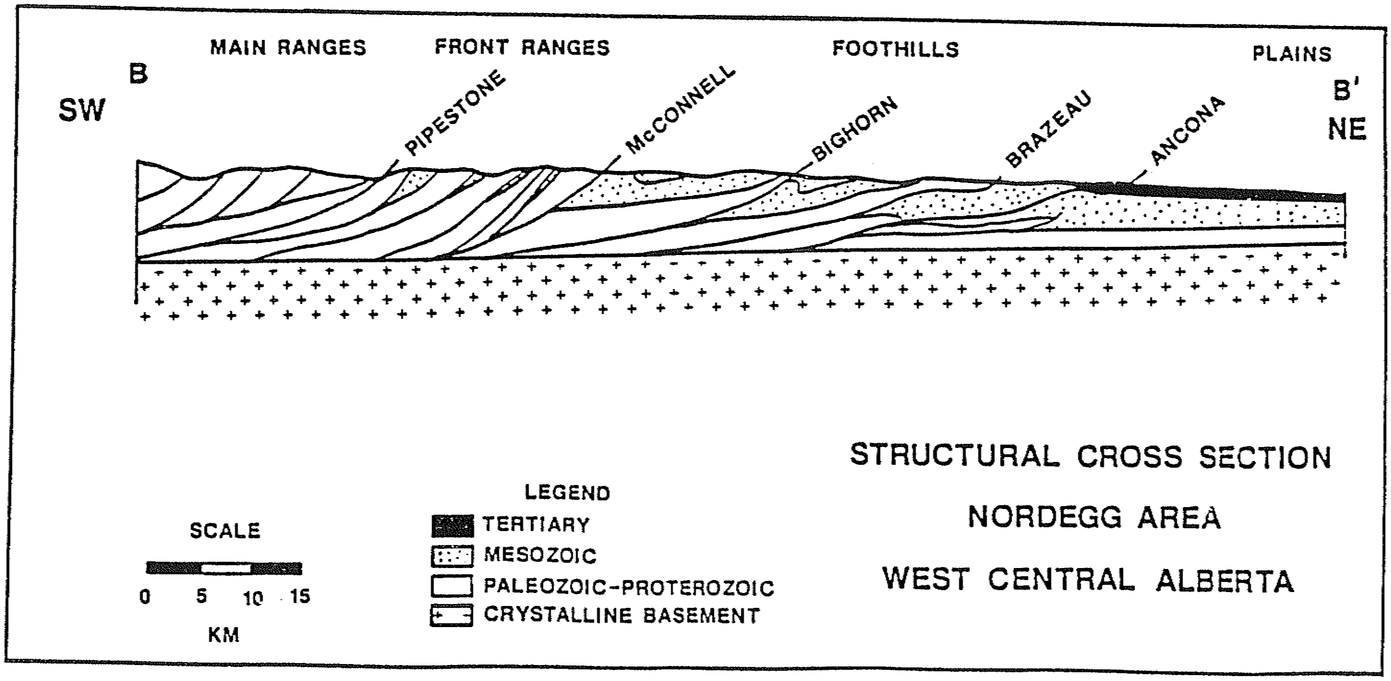
The thesis study area straddles the west-central Plains and the Foothills and Front Ranges of the Rocky Mountains. A simplified geological map and cross-section across the study area is shown in Figs. 5A and 5B.

The structural style of west-central Alberta is classic "thin-skinned" tectonism as there is no evidence that the crystalline basement was directly involved in the deformation. As much as 200 km of crustal shortening has occurred and this has led to imbricate stacking of sheets of structurally competent Paleozoic carbonates to form a series of discrete ranges, each of which is underlain by a major westward-dipping listric thrust fault (Spang et al. 1981). Progressively older strata are exposed at surface as one proceeds westward. Three distinct structural domains can be recognized in the central Rocky Mountain Belt. These are termed the Central Foothills, Front Ranges and Main Ranges and the distribution of each belt is shown in Fig. 5.

The Central Foothills Belt is 50 km wide in west-central Alberta. The eastern margin of the Foothills is marked by the most easterly exposure of deformed Late Cretaceous strata and the western boundary is marked by the



5A



5B

(5)(A) Geologic map of the study area showing location of major thrusts and (B) structural cross section B-B'' (redrawn from Jones and Workum 1978).

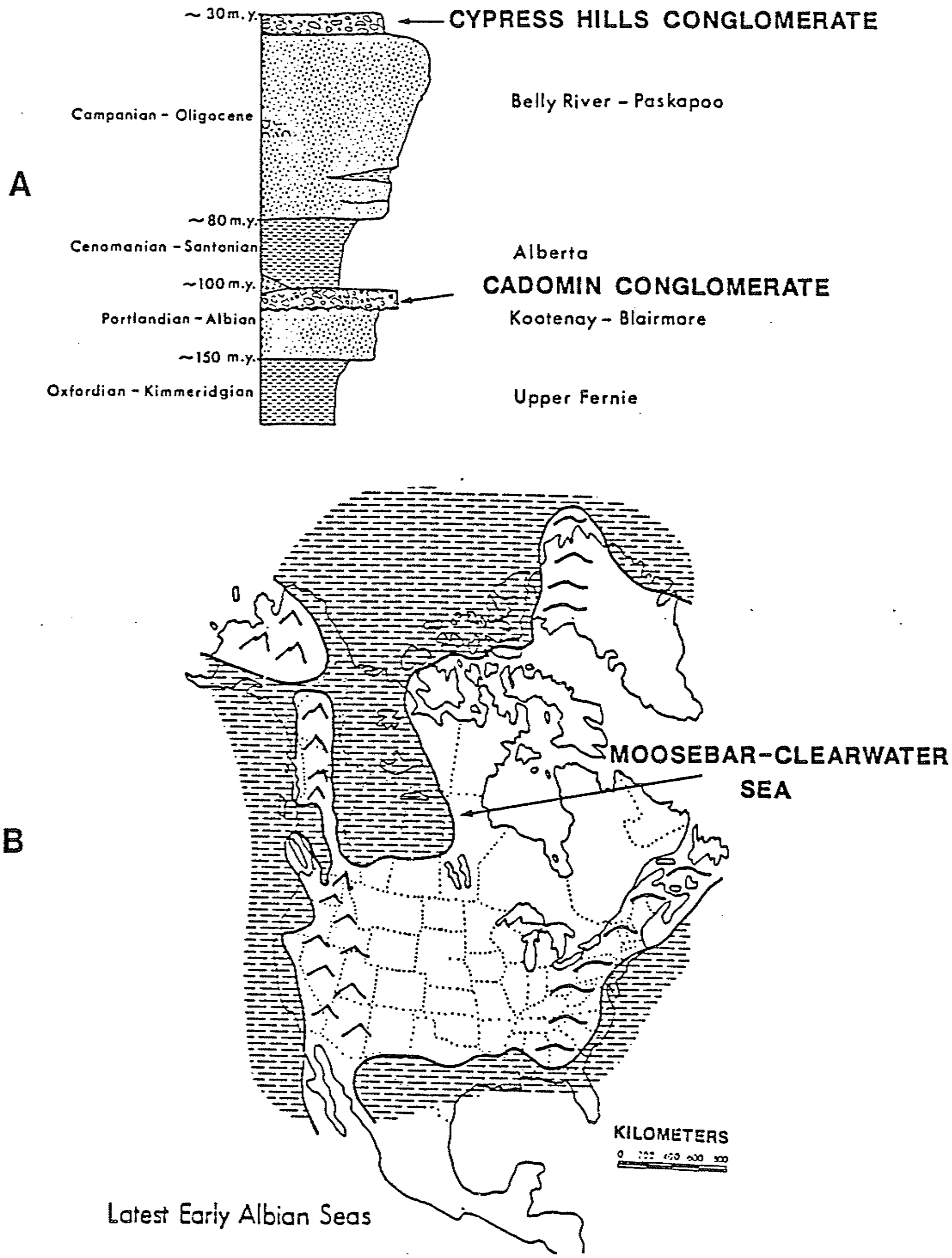
McConnell Thrust (Fig. 5B). The distinctive triangle zone, which marks the eastern limit of the southern Foothills, is not developed in the central Foothills. The Bighorn and Brazeau Ranges are prominent structural culminations in the Foothills belt which have uplifted Paleozoic carbonates to the surface. The thrust faults underlying these ranges can be traced for several hundred kilometers along strike and have experienced horizontal displacements of at least 30 km (Jones and Workum 1978). The Front Ranges are bounded by the McConnell Thrust on the east and the Pipestone Thrust on the west (Fig. 5B). Up to 5 distinct thrusts can be recognized within the central Front Ranges and a striking feature of the geology in this area is the complexity of folding in the incompetent off-reef facies of the Late Devonian. This tight folding is not recognized in the Front Ranges of the Banff area where competent Devonian carbonates form simple westward-dipping thrust repeats (Jones and Workum 1978). The Main Ranges consist of Proterozoic and Paleozoic carbonates, quartzites and slates which are underlain by major thrust faults, similar to those of the Front Ranges.

Most of the outcrops measured in this study are located in the central Foothills where the competent Jurassic - Cretaceous strata is intensely sheared and tightly folded. The amount of horizontal displacement which these outcrop sections have undergone could not be accurately determined although R.H.Workum (pers. comm.) suggested that most have only been displaced several tens of km east of their original location. All of the drill cores examined in this study were from wells drilled in the undisturbed strata of the western Plains.

(C) MESOZOIC-TERTIARY CLASTIC WEDGES IN ALBERTA

The emplacement of thrust sheets in the foreland fold/thrust belt flanking the eastern margin of the collision orogen initiated rapid subsidence in the Western Canadian Sedimentary Basin (Eisbacher et al. 1974). In excess of five kilometers of marine and non-marine clastic strata were deposited in the asymmetric, westward-thickening basin. The sandstones deposited during this time were chert and quartz-rich as they were reworked from uplifted Paleozoic and Proterozoic carbonates and clastics which were exposed in the ancestral Rockies (Schultheis and Mountjoy 1978). Eisbacher et al. (1974) recognized two large scale depositional sequences in the basin, each of which is comprised of a thick basal marine shale overlain by a coarse non-marine interval. They termed the two sequences the Fernie-Kootenay-Blairmore Assemblage and the Alberta-Belly River Assemblage. A schematic diagram showing the age and facies characteristics of each of these successions is shown in Fig. 6A.

The Fernie-Kootenay-Blairmore Assemblage was deposited during the Jurassic to Early Cretaceous and is represented by a wedge of clastic strata which exceeds two kilometers in thickness in the southwestern Foothills. The base of this sequence is marked by the marine Fernie Shales which record a series of Early-Late Jurassic transgressive events. In the southern Foothills, a thick regressive marine sandstone (Morrissey Formation) separates the Fernie shale from the coal-bearing Mist Mountain and Elk Formations of the Kootenay Group (Gibson 1985). In the central foothills, the Fernie shales are overlain by the Nikanassin Formation which appears to be a shallow marine equivalent of the Kootenay interval (Gibson 1985). The Jurassic-Cretaceous boundary occurs near the top of the Kootenay-Nikanassin interval although the exact position of the contact is rarely preserved as subsequent (pre-Cadomin) erosion has removed most of the Jurassic section in the eastern Foothills and adjacent Plains. The overlying Cadomin Formation (Fig. 6A) forms a prominent conglomeratic horizon



(6)(A) Tectonic megacycles in the Western Canadian Sedimentary Basin recognized by Eisbacher et al. (1974)
(B) Albian paleogeography of North America (after Williams and Stelck 1975).

at the base of the Early Cretaceous Blairmore-Luscar interval. The Blairmore-Luscar strata is comprised largely of non-marine strata in the southern and central Foothills but contains a northwestward-thickening, brackish-marine shale (Moosebar Formation) which was deposited during a major southward incursion of the boreal Clearwater Sea into the foreland basin (Fig. 6B). Throughout the Foothills, the upper part of the Blairmore-Luscar Group is comprised of marginal to non-marine strata which are abruptly overlain by marine shales of the Alberta Group.

The Alberta-Belly River-Paskapoo Assemblage spans the Late Cretaceous to Tertiary and is represented by a thick (1-3km) succession of clastic strata in western Alberta. The black marine shales of the Alberta Group represent the basal (marine) phase of this assemblage whereas the overlying, largely non-marine Belly River and Paskapoo Formations comprise the upper part of this second assemblage. Post-Cretaceous erosion has generally stripped off the uppermost part of this assemblage although a thin Oligocene conglomerate, termed the Cypress Hills Formation , unconformably overlies the Late Cretaceous strata in southern Alberta.

CHAPTER 3 STRATIGRAPHIC NOMENCLATURE

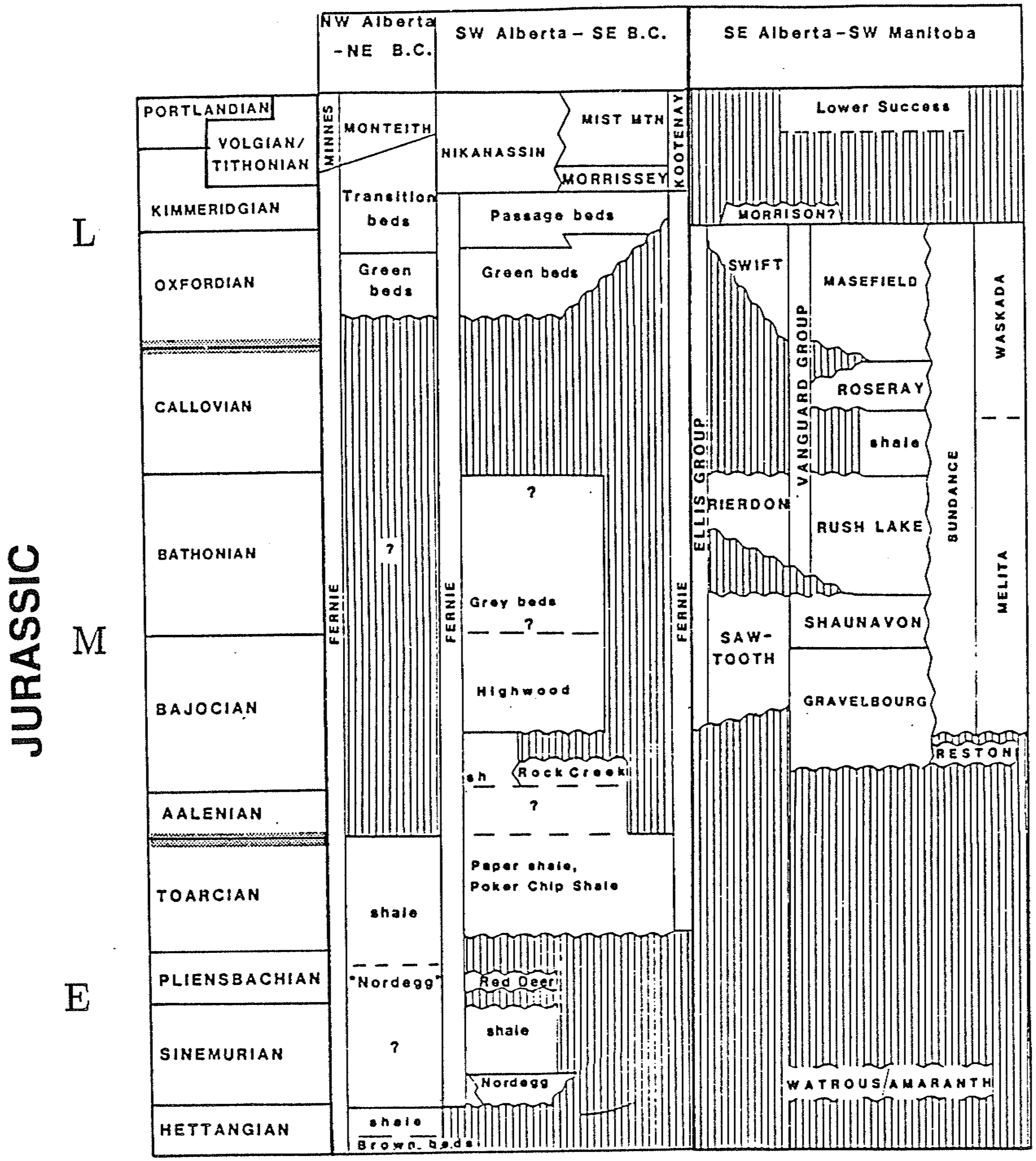
Lithostratigraphic units in the Jurassic-Early Cretaceous clastic wedge of the Alberta Plains and Foothills are described using different nomenclature schemes because the stratigraphic correlations between the strata in these areas remain poorly understood. This chapter will review the development, and current usage, of these nomenclature schemes.

(A) JURASSIC NOMENCLATURE

(i) OUTCROP TERMINOLOGY

The nomenclature scheme currently used to subdivide the Jurassic succession in the Alberta Foothills is shown in Fig. 7. In the southern Foothills, the Jurassic sequence consists of a relatively thin basal marine shale (Fernie Formation) which is overlain by a thick interval of marginal to non-marine, coal-bearing strata termed the Kootenay Group (Gibson 1985). Further north, the basal (Fernie) shale is overlain by a thick sequence of marine and non-marine sandstones which are termed either the Nikanassin Formation (central Alberta) or the Minnes Group (northern Alberta and northeastern British Columbia). The Kootenay-Nikanassin-Minnes interval is not preserved in the southern and central Alberta Plains as it has been truncated by pre-Cadomin erosion.

Leach (1903) first used the term Fernie to describe a recessive-weathering marine shale in the southern Foothills and Jurassic-age ammonites were first recovered from these shales by Whiteaves (1903). The Fernie was formally termed a formation by McLaren (1916) and later upgraded to group status by Frebold (1957) although it is currently considered as a formation (Poulton 1984; Davies and Poulton 1986). The Fernie shale is Early to Late Jurassic in age and comprises a condensed shale sequence which contains numerous



(7) Stratigraphic nomenclature of Jurassic strata in the Western Canadian Sedimentary Basin (after Poulton 1984).

unconformities and hiatal surfaces. Macrofossil (primarily ammonite) and microfossil studies have demonstrated that significant time intervals (e.g. Middle Jurassic) are absent in most of the Foothills exposures (Frebold 1957 1969; Stronach 1984; Davies and Poulton 1986). The term Nordegg Member was introduced by Spivak (1949) to describe an Early Jurassic (Sinemurian) cherty, phosphatic shale and limestone which formed the base of the Fernie in the central Foothills. The same term is employed to describe a succession of coarse sandstones and shallow water carbonates in the west central Plains, near the present erosional edge of the Jurassic strata although the specific correlation has not been confirmed with paleontologic data (Poulton 1984). The term Red Deer Member was used by Frebold (1969) to describe a thin fossiliferous shale and limestone containing Early Jurassic (Pliensbachian) ammonites which is restricted to the central Foothills (Poulton 1984). The term Poker Chip was introduced by Spivak (1949) to describe an Early Jurassic (Toarcian) cherty shale and limestone which is recognized throughout the southern and central Foothills.

The term Rock Creek Member was introduced by Warren (1934) to describe a thin Middle Jurassic (Bajocian) marine sandstone which conformably overlies the Poker Chip Member of the Fernie shale in the type section in the Crowsnest Pass area. Poulton (1984) suggested that this sandstone was only developed in the southern Foothills although Marion (1984) has recovered a Bajocian-age ammonite from the top of a sandstone in west-central Alberta which he termed the Rock Creek Member. Stronach (1984) introduced the term Highwood Member to describe the dark-grey shale of Bajocian age which capped the Rock Creek Member in southern Alberta. The Highwood Member is overlain by a thin light-grey shale (Grey Beds) which contains Bathonian-Callovian (Middle Jurassic) ammonites (Frebold 1957). A second sandy interval, termed the Pigeon

Creek Member, is recognized in the Banff area, approximately 50 meters above the top of the Rock Creek Member (Crockford 1949). A thin grey shale overlying the Pigeon Creek Member in the southern Foothills has been termed the Ribbon Creek Member by Stronach (1984) but its exact age has not been established.

The base the Late Jurassic interval is represented by a thin sequence of glauconitic mudstones which were termed the Green Beds by Frebold (1957). This unit contains an Oxfordian ammonite assemblage and apparently marks a major transgression. In the southern Foothills, the Green Beds are overlain by the Passage Beds which mark the transition between the marine Fernie Formation and the overlying largely non-marine Kootenay Group (Hamblin and Walker 1979; Gibson 1985).

(ii) SUBSURFACE TERMINOLOGY

In southern Alberta, the Jurassic strata are described using the American (Montana) terminology introduced by Cobban (1945). In this scheme, the Ellis Group is divided into the basal Sawtooth Sandstone, the middle Rierdon Shale and the upper Swift Formation (Weir 1949). The Sawtooth is a quartzose sandstone which contains abundant belemnites and a Middle Jurassic (Bajocian-Bathonian) ammonite assemblage. The overlying Rierdon consists of greenish-grey shales and limestones which appear to be Bajocian-Bathonian in age (Poulton 1984). The Swift Formation consists of glauconitic shale and thinly-bedded marine sandstones which are Late Jurassic in age (Hayes 1983).

In the west-central Plains of Alberta, the Jurassic strata is subdivided using outcrop terminology (i.e.,Nordegg, Poker Chip, and Rock Creek Members) although these correlations have generally not been substantiated with paleontologic data. Marion (1984) recovered a Middle Jurassic (Bajocian) ammonite from a shale at the top of a sandstone which he termed the Rock Creek

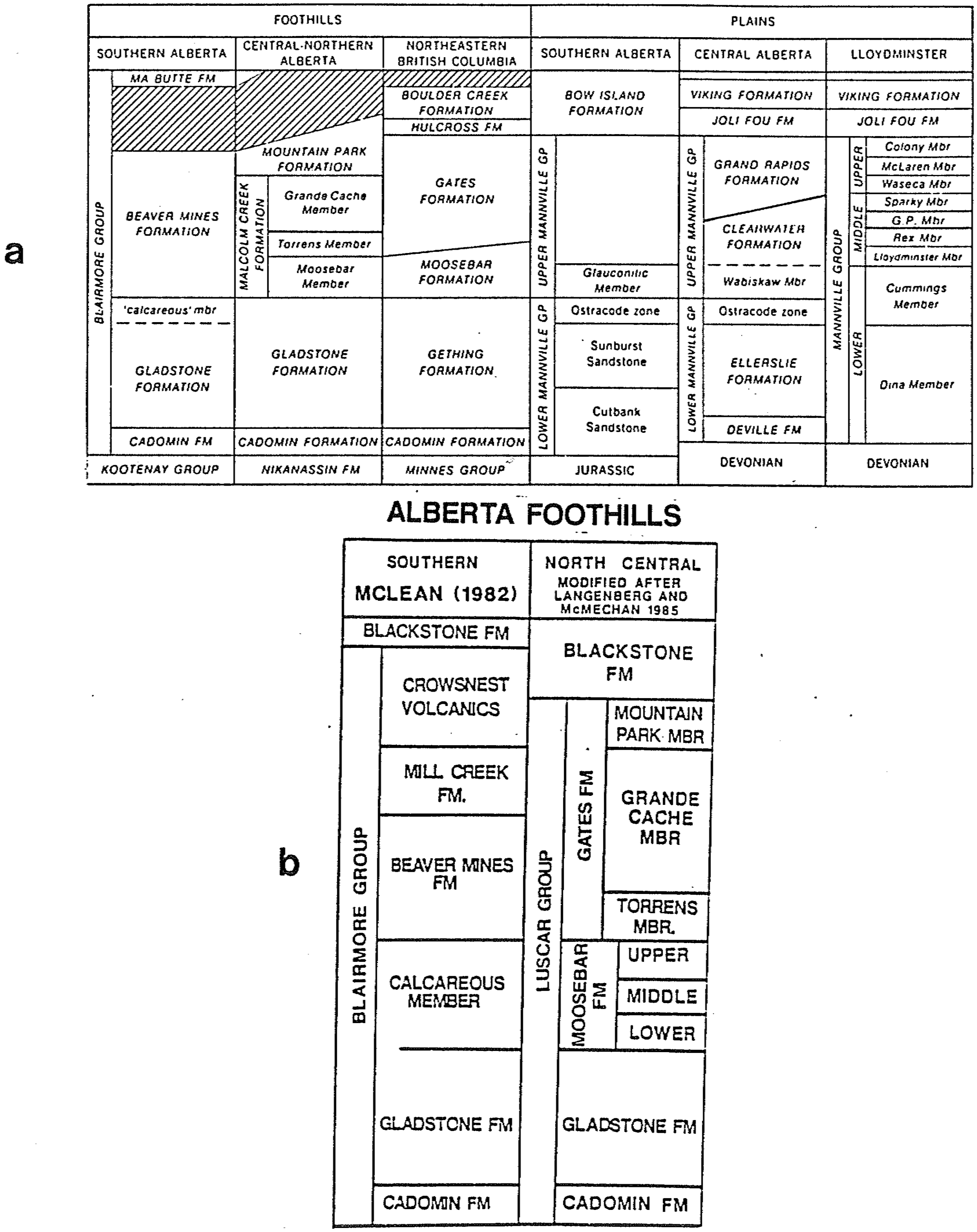
Member and this appears to confirm a correlation with the Sawtooth of the southern Alberta Plains and the type Rock Creek interval of the southern Foothills. Marine shales and sandstones overlying the Rock Creek sandstone were termed "Upper Fernie" by Marion (1984) and palynological data presented in this thesis indicate these strata are equivalent to the Oxfordian Swift Formation of the southern Plains and the Green Beds of the Foothills.

(B) LOWER CRETACEOUS STRATIGRAPHY

(i) OUTCROP

The term Blairmore was first introduced by Leach (1912) to describe a thick succession of continental strata in the Crowsnest Pass area of southern Alberta. This interval was barren of commercial coal seams and separated the lower coal-bearing " Kootanie-series" from an overlying volcanic series which was later termed the Crowsnest Volcanics (McLean 1982). Early researchers considered that Early Cretaceous coal beds in the central Foothills were equivalent to the Kootenay Formation of the Crowsnest Pass area. Mackay (1929) later demonstrated that this correlation was incorrect as the coal measures in the Crowsnest Pass area were below the prominent conglomerate (which he named the Cadomin Conglomerate) whereas the coal measures of the central Foothills were developed above this conglomerate.

In the southern Alberta Foothills (south of the Clearwater River), most early workers (Leach 1912; Rose 1917; Douglas 1950) recognized a five-fold subdivision of the Blairmore. These units included a basal conglomerate, an overlying, non-carbonacous mudstone section, a thin bioclastic limestone and shale interval, and an upper green-colored feldspathic sandstone which was capped by the Crowsnest Volcanics (Fig. 8). Glaister (1959) proposed that the Cadomin conglomerate be awarded formation status and proposed that the Middle



(8) Stratigraphic terminology for Early Cretaceous strata: (A) in the Western Canadian Sedimentary Basin (after McLean 1982) and (B) revised scheme employed in this study.

Blairmore limestone beds be termed the Calcareous Member. Mellon (1967) subdivided the Blairmore into the Gladstone, Beaver Mines and Mill Creek formations and designated a series of type sections in the Crowsnest Pass area (Fig. 8). Moreover, he downgraded the basal (Cadomin) conglomerate and the Crowsnest Volcanics to member status within the Gladstone and Mill Creek Formations respectively. McLean's (1982) recommendations that the Cadomin conglomerate and the Crowsnest Volcanics be re-assigned formation status were accepted in the scheme employed in this study (Fig. 8).

In the Nordegg area of the central Foothills, MacKay (1929) introduced the term Luscar to describe the coal-bearing strata above the basal Cadomin conglomerate. In the same study, the term Mountain Park was introduced to describe the coarser-grained, dark green-colored, non-carbonaceous strata which formed prominent sandstone ledges at the top of the Blairmore succession. Mellon and Wall (1961) later recognized a marine shale tongue within the middle of the Blairmore interval in the Cadomin area which they correlated with, and named after, the Moosebar Shale which outcropped along the Peace River Canyon (McLearn 1923).

The stratigraphic relationship and discrimination between the Luscar and Mountain Park intervals has been debated at length and much of the difficulty stems from the fact that no type section was designated for these units and they were only briefly described by MacKay (1929). McLean (1982) recommended that the term Luscar be abandoned and proposed a new name for the Upper Blairmore interval (Malcolm Creek Formation) which was subdivided into the Moosebar, Torrens and Grande Cache Members. Langenberg and McMechan (1985) argued to retain and upgrade the term Luscar to group status and subdivided it into the Cadomin, Gladstone, Moosebar and Gates Formations. They also suggested that the Gates Formation could be subdivided into the Torrens, Grande Cache and

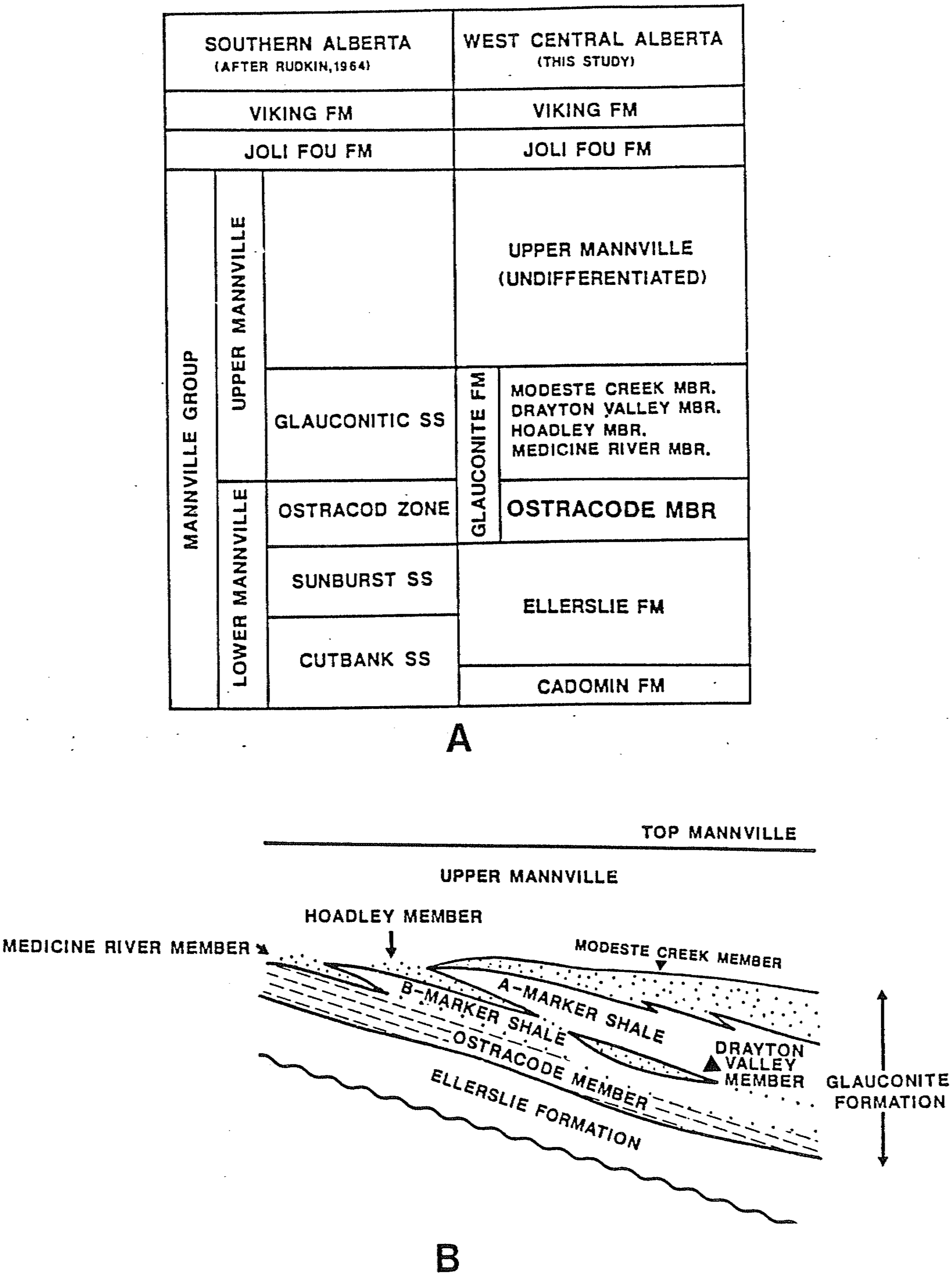
Mountain Park Members.

The study area of this thesis straddles the boundary between southern Foothills, where McLean's (1982) terminology was employed, and the central Foothills, where a modified version of Langenberg and McMechan's (1985) scheme is employed (Fig. 8). The stratigraphic relationship between the elements of these two nomenclature schemes will be discussed in Chapter 6.

(ii) SUBSURFACE TERMINOLOGY

The term Mannville was first introduced by Nauss (1945) in east central Alberta to describe the Early Cretaceous clastic succession between the Devonian carbonates and the marine shales of the Late Cretaceous Colorado Group. Badgley (1952) elevated the term to group status and extended its usage to include the McMurray, Clearwater and Grand Rapids strata of northeastern Alberta. In southern Alberta, early researchers (i.e., Loranger 1951; Workman 1959; and Glaister 1959) were able to correlate and subdivide the Blairmore and Mannville succession on the basis of a calcareous marker horizon bearing a distinctive ostracode assemblage. In central Alberta, Mellon and Wall (1961) and Mellon (1967) correlated elements of the Mannville and Blairmore successions on the basis of a thin marine shale in the middle of the interval.

Subdivision of the Mannville in the subsurface is severely hampered by a plethora of local field names, miscorrelated regional markers, and complex facies variations which render simple "layer-cake" nomenclature schemes useless. In west-central Alberta, Rudkin (1964) subdivided the Mannville Group into five units (Fig. 9A) which include the basal Ellerslie Formation, the Ostracode Zone, the Glauconitic Sandstone and the Upper Mannville (undifferentiated). As presently employed, this terminology does not conform to the North American Stratigraphic Code as the rank of several units is unclear.



SOUTHERN ALBERTA (AFTER RUDKIN,1964)			WEST CENTRAL ALBERTA (THIS STUDY)	
VIKING FM			VIKING FM	
JOLI FOU FM			JOLI FOU FM	
MANNVILLE GROUP	UPPER MANNVILLE		UPPER MANNVILLE (UNDIFFERENTIATED)	
		GLAUCONITIC SS	GLAUCONITE FM	MODESTE CREEK MBR. DRAYTON VALLEY MBR. HOADLEY MBR. MEDICINE RIVER MBR.
	LOWER MANNVILLE	OSTRACOD ZONE		OSTRACODE MBR
		SUNBURST SS	ELLERSLIE FM	
		CUTBANK SS		
			CADOMIN FM	

(9)(A) Subsurface stratigraphic nomenclature (revised) for the Early Cretaceous strata examined in this thesis and (B) schematic diagram showing the stratigraphic relationship of the three marine sandstones in the Glauconite Formation.

However, since these terms are firmly entrenched in the geological literature of western Canada, it is recommended that their status be clarified, and redefined if necessary, rather than being abandoned altogether.

The term Ellerslie Series was first introduced by Hunt (1950) to describe the Early Cretaceous strata below the Ostracode Zone in the Whitemud field, located south of Edmonton. The Ellerslie was later awarded member status by Williams (1963) who considered it as part of the McMurray Formation. The reason for differentiating the Ellerslie Member from the remainder of the McMurray Formation was not clearly stated by Williams (1963) as Hunt's original (1950) definition of the Ellerslie included all the Early Cretaceous strata below the Ostracode marker, and not just the upper portion of the interval. It is recommended that the term Ellerslie be elevated to formation status and that it includes the entire Early Cretaceous section beween the pre-Cretaceous unconformity and the overlying Ostracode interval.

The term Ostracode Zone was introduced by Loranger (1951) to describe a thin bioclastic shale in central Alberta which contained a distinctive fresh to brackish-water ostracode assemblage. This shale was correlated with the thin bioclastic limestone in the Blairmore-Mannville interval of southern Alberta which contained a similar fossil assemblage (although the stratigraphic relationship between these two lithologies has never been clearly established). A recent study by Finger (1983) noted that this is a facies-controlled faunal assemblage comprised of long-ranging species which is of limited use as a precise biostratigraphic datum. Regardless of their relationship to the Ostracode limestones of southern Alberta, the bioclastic shales comprising the Ostracode interval are a excellent lithostratigraphic marker in the type area (central Alberta Plains) and clearly merit formal status. However, in its present form, the term Ostracode Zone is inappropriate as zone is a precise biostratigraphic term which should not be used in lithostratigraphic schemes. It is recommended that this interval be redefined as Ostracode Member and included as the basal part of the (revised) Glauconite Formation, as defined below.

The term Glauconitic Sandstone was introduced by Layer (1949) to describe a highly glauconitic chert-rich sandstone in the Edmonton area although its status has never been clearly stated. Since this term is presently used to describe a wide range of lithologies, it is recommended that the lithic designation be dropped and the interval redefined as the Glauconite Formation. It is also recommended that the Ostracode Member (redefined above) be included as the basal unit in the Glauconite Formation. In the thesis study area, four distinct marine sandstones are developed in the the Glauconite Formation and these are awarded member status. Formal names and proposed type sections for these sandstones are presented in chapter 6.

The base of the upper Mannville interval is defined at the base of the first coal or carbonaceous shale capping the sandstones of the Glauconite Formation. The upper part of the Mannville was not subdivided by Rudkin (1964) or in this study although local marker horizons (e.g.Medicine River Coal) are recognized by some operators.

CHAPTER 4 PREVIOUS SEDIMENTOLOGICAL STUDIES

(A) FERNIE FORMATION

The sedimentology of the Fernie strata has not been extensively studied as most researchers, to date, have focused on the biostratigraphy and regional correlations within the interval. The thickness and character of the Jurassic succession changes dramatically between the Plains and Foothills and, in central Alberta. Regional paleogeographic reconstructions proposed by Loranger (1951), Springer et al.(1964), Carlson (1968) and Poulton (1984) all recognized that the Jurassic interval thickens westward and that the deep-water, open-marine shales found in the Foothills are equivalent to shallow-marine sandstones and carbonates in the western Plains. These regional studies also indicate that a broad, shallow cratonic sea centered in the Williston basin was connected to open ocean by an east-trending trough which traversed what is now southern Alberta and northern Montana.

Complex facies variations and numerous unconformities are recognized within the Jurassic interval in the Foothills and Plains. In central Alberta, the Jurassic strata unconformably onlap Triassic or Paleozoic strata and the contact with the overlying Cretaceous strata is generally marked by a major unconformity which can be traced throughout the basin. The Early and Middle Jurassic sandstones are highly quartzose and were probably derived from an eastern (Shield) source (Springer et al. 1964) whereas some of the Late Jurassic sandstones (e.g.,Kootenay-Nikanassin) are chert-rich and were probably derived from a western (Cordilleran) source (Gibson 1985). This interval thus records the evolution of the basin from a passive margin to foreland basin although the transition beds are only preserved in the Foothills as pre-Cretaceous erosion has truncated the Late Jurassic succession in the western Plains.

Only a few detailed sedimentological studies of Jurassic strata have been conducted in the thesis area. Hopkins (1981) studied a series of incised channel-fill sandstones in the Medicine River area (TWP39 R3W5) and suggested that these sandstones were deposited under non-marine (fluvial and aeolian) and brackish to marine subaqueous conditions. He recognized several unconformities within the valley-fill succession and outlined the problems with resolving the age (i.e. Jurassic or Lower Cretaceous) of these sandstones. He correlated the highly quartzose, channel sandstones with mineralogically similar sequences (Roseray-Success Formations) of southwestern Saskatchewan and suggested that stratigraphic variations in framework composition recorded temporal fluctuations in climate.

Marion (1984) studied the Rock Creek, Upper Fernie and Ellerslie strata in west-central Alberta and concluded that the Middle Jurassic (Bajocian) Rock Creek sandstones were deposited in a storm-dominated shelf setting and that the overlying Late Jurassic (Oxfordian-Kimmeridgian) Upper Fernie shales were deposited in a deep shelf setting during a major marine transgression. He interpreted the lower part of the Ellerslie as fluvial deposits and suggested that the upper part of the Ellerslie was deposited under brackish-marine conditions.

Stronach (1984) studied the Fernie Formation in the Foothills and considered that the entire Jurassic interval was deposited on a shallow, westward-dipping marine shelf. He recognized 5 distinct shallowing-upward cycles within the Fernie and noted that bottom sediment conditions gradually changed from anaerobic to dysaerobic to aerobic within each cycle. Each cycle was terminated by a condensed sequence which contained glauconite, calcite and phosphate. He suggested that the organic-rich Poker Chip shales were deposited on an anaerobic shelf where wave energy was damped at the shelf edge whereas the Rock Creek Member represented a tidally-influenced, shallow subtidal shelf setting. In the upper part of the Fernie (Pigeon Creek Member), Stronach (1984) suggested that the parallel-laminated and hummocky cross-stratified sandstones were deposited by storms and sediment gravity flows (turbidity currents) which traversed a shallow (non-tidal) shelf.

The only subsurface study of the Upper Fernie strata was restricted to southern Alberta Plains where the unit is termed the Swift Formation. Hayes (1983) documented that the Swift consisted of a basal shale overlain by thinly bedded "ribbon sandstones" which were dark grey and bioturbated at the base and tan to light grey and weakly bioturbated near the top. He noted abundant flaser and wave ripple lamination and minor trough cross - stratification within the sandy interval and interpreted the unit as shallow wave and current-influenced shelf bar deposits.

(B) BLAIRMORE-LUSCAR-MANNVILLE

Numerous sedimentologic and petrographic studies of the Blairmore-Mannville strata in the Alberta Plains have been published although most of these are local field studies which are of limited use for resolving the regional correlations and paleogeography. Due to space limitations however, only a few regional studies and those conducted within the thesis study area will be discussed in this section.

The first detailed regional study of the Mannville succession was published by Glaister (1959). He established correlations between various sandstones developed in the Mannville (Glauconite, Ellerslie, Cutbank, Sunburst etc.) across Alberta on the basis of proximity to the the Calcareous Member-Ostracode Zone marker. He also documented pronounced changes in thickness and petrographic composition of the various units across the study area. Williams (1963) established correlations between the Ellerslie-Glauconite-Upper Mannville strata of west-central Alberta and the McMurray-Clearwater-Grand Rapids succession of northeastern Alberta. He noted that the depositional setting changed from fluvial (Lower McMurray) to estuarine (Ellerslie-Upper McMurray) to open marine (Glauconite-Clearwater) and back to non-marine (Grand Rapids-Upper Mannville). Williams (1963) also recognized distinctive light and heavy mineral assemblages within the Mannville and suggested that the change in framework and heavy mineral composition reflected a change from Shield to Cordilleran provenance .

Rudkin (1964) informally divided the Mannville-Blairmore Group into lower (base Cretaceous to top Ostracode Limestone) and upper (top Ostracode Limestone to base Colorado Group) units and constructed regional isopach maps for these intervals across the western Canadian Plains. He suggested that the base of the lower Mannville interval represented non-marine (fluvial) deposits across the southern Plains and that the overlying Ostracode Limestone was deposited in a fresh to brackish-water lake or bay. Rudkin (1964) also recognized a thin marine interval at the base of the upper Mannville unit in central Alberta (Glauconitic Sandstone) but noted that the rest of the upper Mannville was comprised of non-marine facies in southern and central Alberta.

Mellon and Wall (1961) and Mellon (1967) published detailed petrographic-stratigraphic studies of the Blairmore sandstones in the Foothills. They subdivided the interval into three units, based on pronounced changes in the light and heavy mineral composition of the sandstones and the floral content of the shales . The lower interval, represented by the Gladstone Formation, consisted of quartz and chert-rich, non-marine sandstones which contain an ultrastable heavy mineral assemblage, presumably reflecting a recycled sedimentary provenance. These sandstones were capped by brackish-lacustrine limestones of the Calcareous Member (Mellon 1967). The middle unit, termed the Beaver Mines Formation, consisted of non-marine feldspathic sandstones which contained a metastable heavy mineral assemblage, reflecting a largely volcanic provenance. This interval contained a "primitive" floral assemblage of gingkos, ferns and conifers. The upper unit (Mill Creek Formation), which contained non-marine, quartzose sandstones and a dicotyledonous angiosperm plant fauna, was absent in the Plains and central-northern Foothills (Mellon and Wall 1961).

Cameron (1965) attempted to resolve the Mannville-Blairmore correlation problems by comparing the major element chemical composition of shale and sandstone samples from a series of outcrop and borehole locations. He noted that the sodium content was the most reliable indicator of provenance which was least affected by grain size variations. He grouped the Gladstone and overlying Calcareous Member of the Foothills, and the Ellerslie-Ostracode-Glauconitic interval of the subsurface, in his "lower soda" group (mean .29% by weight) and suggested that the low soda content reflected a highly weathered or recycled sedimentary(Cordilleran) provenance. His "middle soda" interval, which contained much higher sodium values (mean 2.29% by weight), included the Beaver Mines of the southern Foothills and the Upper Mannville of the plains. Cameron (1965) suggested that "middle soda group" in western Alberta had a mixed igneous-sedimentary Cordilleran provenance and noted that quartzose Shield-derived material was interbedded with the soda rich "middle soda group" in eastern Alberta. His "upper soda" group (mean .82% by weight) which included the upper Blairmore (Ma Butte equivalent) in the Foothills and the Viking and Basal Colorado Sandstones of the Plains.

Rapson (1965) studied the petrography of a suite of Late Jurassic-Early

Cretaceous sandstones exposed in outcrop in the southern Alberta Foothills. She suggested that most of the Kootenay, Cadomin and Gladstone sandstones had been eroded from uplifted Early Mesozoic, Paleozoic and Proterozoic strata in the Main Ranges. She also recognized that a minor igneous and metamorphic component may have been derived from the Selkirk Metamorphic Province and from Permian-Pennsylvanian volcanic terranes in south-central British Columbia.

McLean (1977) and Schultheis and Mountjoy (1978) studied the Cadomin Formation in outcrop along the length of the Rocky Mountain Foothills and suggested that the major unconformity at the base of the conglomerate represented a pediment surface. Both studies reported that the interval thickened westward and that this was accompanied by an westerly increase in maximum clast size. Mclean (1977) suggested that most of the detritus was deposited in alluvial fan and braided river evironments. The notable absence of igneous and metamorphic detritus was cited as evidence that the bulk of material was derived from the Main Ranges, west of the Rocky Mountain Trench (McLean 1977; Schultheis and Mountjoy 1978).

Mclean and Wall (1981) studied the sedimentology and microfossil content of outcrops of the Gladstone and Moosebar Formations in the central and northern Foothills. They reported that the Calcareous Member at the top of the Gladstone Formation could be recognized throughout their study area. This interval contained shaly limestones which yielded a fresh to brackish-water microfossil assemblage in the southern Foothills and wave-ripple-laminated shales and thin coal beds, associated with brackish to restricted marine microfossils, in the central and northern Foothills. The Moosebar Formation, as defined by McLean and Wall (1981), contained an open marine (calcareous and agglutinated) foraminifera assemblage and was not developed in the southern Foothills. They suggested that the Torrens Member represents the progradation of a wave-dominated shoreline as the Moosebar Sea retreated from the basin.

Finger (1983) studied the microfossil assemblage of the Ostracode Zone of west-central Alberta and concluded that the " spatial variations in assemblage compositions and lithology suggest a diversity and mixture of coastal environments including lakes, rivers, swamps, lagoons and estuaries ".

Taylor and Walker (1984) measured several Blairmore outcrops in the south-central Foothills and noted that the Moosebar Formation could be recognized as far south as Elbow Falls outcrop, located approximately 70 km southwest of Calgary. They reported that carbonaceous fluvial strata of the Gladstone Formation were overlain by brackish water shales, sandstones and limestones of the Calcareous Member in the southern Foothills and by brackish-marine shales of the Moosebar in the central Foothills. They also suggested that the Calcareous Member was stratigraphically equivalent to the basal part of the Moosebar Formation. In the Crescent Falls outcrop, Taylor and Walker (1984) reported brackish to freshwater ostracodes, gastropods and pelecypods at the base of the Moosebar and open marine shales with agglutinated forams interbedded with bioturbated and swaley-cross stratified sandstones at the top of the interval. This outcrop was remeasured in this study and a more complete description and interpretation will follow in the section on outcrop facies and correlations (Chapter 6).

Burden(1984) sampled Lower Mannville strata for palynomorphs from widely separated outcrops in northern Montana and northern Alberta and sampled several cores in central Alberta to relate to the subsurface terminology. His study emphasized that lithostratigraphic units within the Mannville were probably diachronous as the Calcareous Member and Sunburst Sandstone are Barremian in age in Montana whereas the Ostracode-Ellerslie interval in central Alberta ranges as young as Aptian (Burden 1984).

Chiang (1984) studied the sedimentology of the Glauconite Formation in central Alberta and interpreted a northeast-trending sand trend (Hoadley Complex) as a barrier bar capped by aeolian dune sands which was intensely dissected by tidal channels. Chiang (1984) and Reichenbach (1982) also recognized that northeast-trending incised channel sandstones in the Medicine River area (20 km south of the Hoadley) as distributary channels which fed the Hoadley Barrier, although neither explained why the channel trend was oriented parallel to the paleoshoreline.

Young and Doig (1986) reported that the sandstones in the channels dissecting the Hoadley trend contained markedly different light and heavy mineral assemblages and used this as evidence that these channels are not age-equivalent tidal channels cutting the barrier bar, as Chiang (1984) suggested, but rather younger incised fluvial channels which record a late-stage drop in relative sea level.

The most comprehensive regional study of the Mannville Group in the Alberta Plains was published by Jackson (1984). He subdivided the interval into 5 units which include the Lower Mannville, Ostracode-Upper Gething, Bluesky-Glauconite, and the Upper Mannville (undifferentiated). He constructed paleogeographic maps for each interval, based on core facies and net sand isopach maps. His correlations and overall interpretations were similar to those forwarded by Rudkin (1964) although he differs on several key points. Jackson (1984) recognized that a significant thickness of marine to brackish-water sediments is developed at the top of the lower Mannville (Ellerslie) interval, directly below the main Clearwater-Glauconite marine shale. He noted that this brackish interval was thickest along the axis of the ancestral Edmonton and Spirit River Channels and suggested that the marine waters in northeastern Alberta spilled through a break in the Aptian Ridge thus changed the river channel into a drowned river valley (estuary), as described previously by Williams (1963) and Rudkin (1964). However, more recent studies (e.g. Banerjee 1986) have reported that bioturbated, brackish-water sediments are developed throughout the Lower Mannville succession in the Edmonton Channel. This suggests that, in central Alberta, the Edmonton "Channel" was actually a broad, shallow restricted-marine embayment, rather than an incised fluvial channel.

The second important contribution made by Jackson´s (1984) study is that the Bluesky-Glauconite interval was deposited during multiple transgressive-regressive events. Although he did not resolve the age relationship between the sandstones deposited during these events, he did outline the distribution of several marine sandstone trends within this interval. In addition, this study recognized the stratigraphic equivalence of the regressive marine sandstones and conglomerates comprising the Upper Mannville (Fahler Member) in northwestern Alberta with the Grand Rapids sandstone of northeastern Alberta. These correlations had been inferred by Rudkin (1964) although the specific correlation, and implications for basin paleogeography, had not been established.

CHAPTER 5 DEPOSITIONAL FACIES

Twelve outcrop exposures and approximately 200 drill cores of Fernie and Blairmore-Mannville strata were compiled in this study. These strata were described in terms of color, grain size, the presence or absence of physical and biogenic sedimentary structures, and the nature of contacts between the various lithologies. Drafted sections of each core and outcrop are included in Appendix 3. This descriptive lithologic data was "distilled" into a series of recurrent depositional facies. The salient characteristics of, and interpretations proposed for, each depositional facies are summarized in the following section.

(A) JURASSIC FACIES

Six distinctive depositional facies were recognized in the Jurassic strata examined and several of these have been subdivided into several subfacies. A brief description and interpretation of each facies is outlined in Table 1 and a summary of micropaleontological data and interpretations is tabulated in Table 2. These facies have been termed J-1 to J-6 although it is emphasized that the numbers are descriptive only and do not have any stratigraphic significance.

(i) J-1 FACIES, CLEAN SHALE (<10% SILTSTONE/SANDSTONE INTERBEDS)

The J-1 facies consists of massive to thinly bedded shale which contains rare (< 10%) sharp-based sandstone laminae. This facies is divided into two subfacies on the basis of color.

The J-1A sub-facies consists of a light grey to green, slightly dolomitic waxy shale which is non-bioturbated and devoid of any sedimentary structures. This facies is generally non-fossiliferous although scattered belemnites were

FACIES		DESCRIPTION	STRATIGRAPHIC DISTRIBUTION	INTERPRETATION
J1 Shale (less than 10% siltstone)	J1A	Light grey-green, waxy texture, crudely bedded, rare belemnites	Poker Chip Member Upper Fernie	Open marine
	J1B	Black-dark grey brown, thinly laminated, fissile, non bioturbated	Poker Chip Member (Foothills)	Open marine
J2 Interbedded, sandstone siltstone & shale	J2A	Light ribbon facies, (tan-light grey colored) non to weakly bioturbated thin (.5-2cm) bedded	Upper Fernie	Restricted-marine?
	J2B	Dark ribbon facies, (dark grey to black) weak to moderately bioturbated abundant synaerisis cracks,	Upper Fernie	Brackish-marine
	J2C	Highly bioturbated sandy mudstone	Rock Creek Member	Open marine
J3 Clean, quartzose sandstone (less than 10% interbedded shale) *	J3A	Very fine to fine grained, ultraquartzose, abundant current, & possible flaser ripple lamination	Upper Fernie	Open marine shallow shelf wave/tide influenced off-shore bar facies
	J3B	Upper fine to medium grained, high angle foresets (probably trough cross stratification)		
	J3C	White, very fine to fine grained sandstone massive, structureless, non bioturbated		
	J3D	Very fine to fine grained sandstone, parallel and low angle convergent laminations common, no high angle foresets		
J4 Argillaceous sandstone		Highly bioturbated, slightly to very argillaceous sandstone, high density, high diversity trace fossil assemblage trace glauconite.	Rock Creek Member	Open marine
J5 Argillaceous cherty limestone and dolomite		Lime & dolomite wackestone-mudstones, trace crinoids, sponge spicules, highly silicified, tightly cemented	Nordegg Member	Shallow-subtidal
J6 Pyritized Regolith-Breccia		Angular chert, carbonate and sandstone clasts in a green-grey sandy shale matrix, extensive pyrite fracture infill	Top Nordegg Top Rock Creek Middle Upper Fernie	Paleosol horizons

Table 1. Description, Stratigraphic Distribution and Interpretation of Jurassic Lithofacies, West Central Alberta

* Clean- non-argillaceous

SAMPLE /LOCATION /DEPTH	FACIES	STRATIGRAPHIC UNIT	MICROPALEONTOLOGY	PALYNOLOGY
			ENVIRONMENT - AGE	ENVIRONMENT - AGE
JURASSIC SAMPLES				
SH-2 8-33-40-3W5, 2128m	J2A	UF	NR	NR
SH-4 10-29-56-11W5, 6032m	J1A	PC	Prob. Marine Indeterminate Age	Open Marine Late Jurassic
SH-5 10-18-55-12W5, 1933m	J2B	UF	NR	Prob. Marine Late Jurassic
SH-6 4-33-39-5W5, 2337m	J2B	UF	NR	Prob. Non Marine Indeterminate Age
SH-13 5-34-48-12W5, 2492m	J2B	UF	Prob. Shallow/Restricted Marine Jur.or Cret.	Prob. Marine Prob. L. Cret.
SH-31 12-32-42-9W5, 2650m	J2B	UF	NA	Shallow Marine M. Jur. - E. Cret.
SH-42 6-14-46-10W5, 2420m	J2B	UF	NA	Marine L. Oxford. –– E. Kimm
SH-64 8-35-49-12W5, 7587'	J2B	UF	NA	Nearshore Marine ? Mid Oxford.
SH-65 8-35-49-12W5, 7640'	J2B	UF	NA	Nearshore Marine L. Callovian - Mid Oxford.
SH-74 8-30-50-13W5, 2433m	J2B	UF	NA	Non-Marine L. Jur. - Cret.
SH-75 8-30-50-13W5, 2450m	J2B	UF	NA	Non-Marine L. Oxford - ? E. Kimm.
SH-86 10-24-54-13W5, 6406'	J2A	UF	NA	Non-Marine ? Mid Jur. - E. Cret.
SH-87 10-24-54-13W5, 6460'	J2B	UF	NA	Marine Mid. Callovian
SH-88 10-24-54-13W5, 6505'	J2C	PC	NA	Restricted Marine Bath. –– E. Callov.
SH-89 2-2-55-13W5, 6475'	J2B	UF	NA	Nearshore Marine Prob. Mid. Oxford.

Table 2: Summary of Micropaleontology/Palynology Interpretations Jurassic Strata, West-Central Alberta.

NA - not analyzed *NR - No Recovery* *UF - Upper Fernie* *P C - Poker Chip* present in one core (i.e. 1-2-54-8W5). Subfacies J1B is dark grey to black in color and was only observed in the outcrop section on Prairie Creek where it is developed below and above the thin quartzose sandstone which was mapped as the Rock Creek Member.

The J-1 facies comprises a thin, laterally extensive shale which is correlated with the Early Jurassic Poker Chip Member (Fernie Formation) in the Foothills, according to the Alberta Energy Resources Conservation Board. However, the single sample of this shale which was processed for microfossils in this study (# 4, Table 2) contained a Late Jurassic, open-marine pollen assemblage and (probable) marine foram assemblage. This shale was resampled and by an industry micropaleontologist who interpreted the meagre microfossil assemblage as Early Jurassic in age. However, the specific species data and environmental interpretations proposed for this sample were still confidential at the time this thesis was written and this apparent discrepancy has not yet been resolved.

INTERPRETATION

The absence of diagnostic trace or body fossils or sedimentary structures precludes a detailed interpretation of depositional environment. The fine-grain size and presence of belemnites (e.g., 11-2-54-8W5) and marine foraminifera (e.g.,10-29-56-11W5) suggests that subfacies J-1 probably represents a relatively deep, open-marine environment.

The differences in color probably reflect the degree of oxygenation of the substrate during deposition. Marion (1984) and Stronach (1984) interpreted the dark-colored Poker Chip shales in outcrop as (anaerobic) shelf or slope deposits. The lighter colored (J1A) facies in western Alberta Plains was probably deposited under well-oxygenated conditions in shallower water.

(ii) J-2 FACIES, INTERBEDDED SANDSTONES AND SHALES

The J-2 facies (Table 1) consists of intercalated sandstones, siltstones and shales which are either thinly laminated and non to weakly bioturbated (J-2A and J2B) or highly bioturbated (J-2C). This facies is restricted to the Upper Fernie and Rock Creek intervals.

The J-2A sub-facies, informally termed the light ribbon facies, consists of subequal proportions of thin (less than 2 cm) light grey siltstone and sandstone laminae interbedded with tan-colored shale (Fig. 10C). The sandstone laminae are sharp-based, non-bioturbated, and contain wave and current ripple lamination. The two shale samples (SH-2, SH-86, Table 2) from this sub-facies which were processed for microfossil/palynology content were both barren.

The J-2B (dark-ribbon) sub-facies is a medium to dark grey shale which contains varying proportions (10-80%) of thin (0.1-5.0 cm) sharp-based sandstone laminae. Most sandstone laminae contain current and/or wave ripple lamination (Fig. 10B). Pyrite nodules, small scale normal faults, soft sediment deformation structures and scattered small Planolites, Chondrites, Skolithos, Helminthopsis and Teichichnus burrows, and rare synaeresis cracks, were also observed in this facies. In cores where a thick (greater than 10m) interval of the J2B facies is developed, several meter-scale coarsening and thickening-upward sequences are recognized and these are typically capped by a cm-thick pebbly, glauconitic mudstone. The J2B facies is generally devoid of fossils although abundant belemnites were reported in the 6-14-46-10W5 core. Several shale samples (SH-5, 6, 13, 31, 42, 64, 65, 74, 75, 87 and 89) from the J-2B facies were analyzed for microfossils and these data are compiled in Appendix 6 and summarized in Table 2. Only two samples were analyzed for foraminifera content and of these, one (SH-5) was barren. The other sample (SH-13) contained a sparse foraminiferal assemblage which was interpreted as a

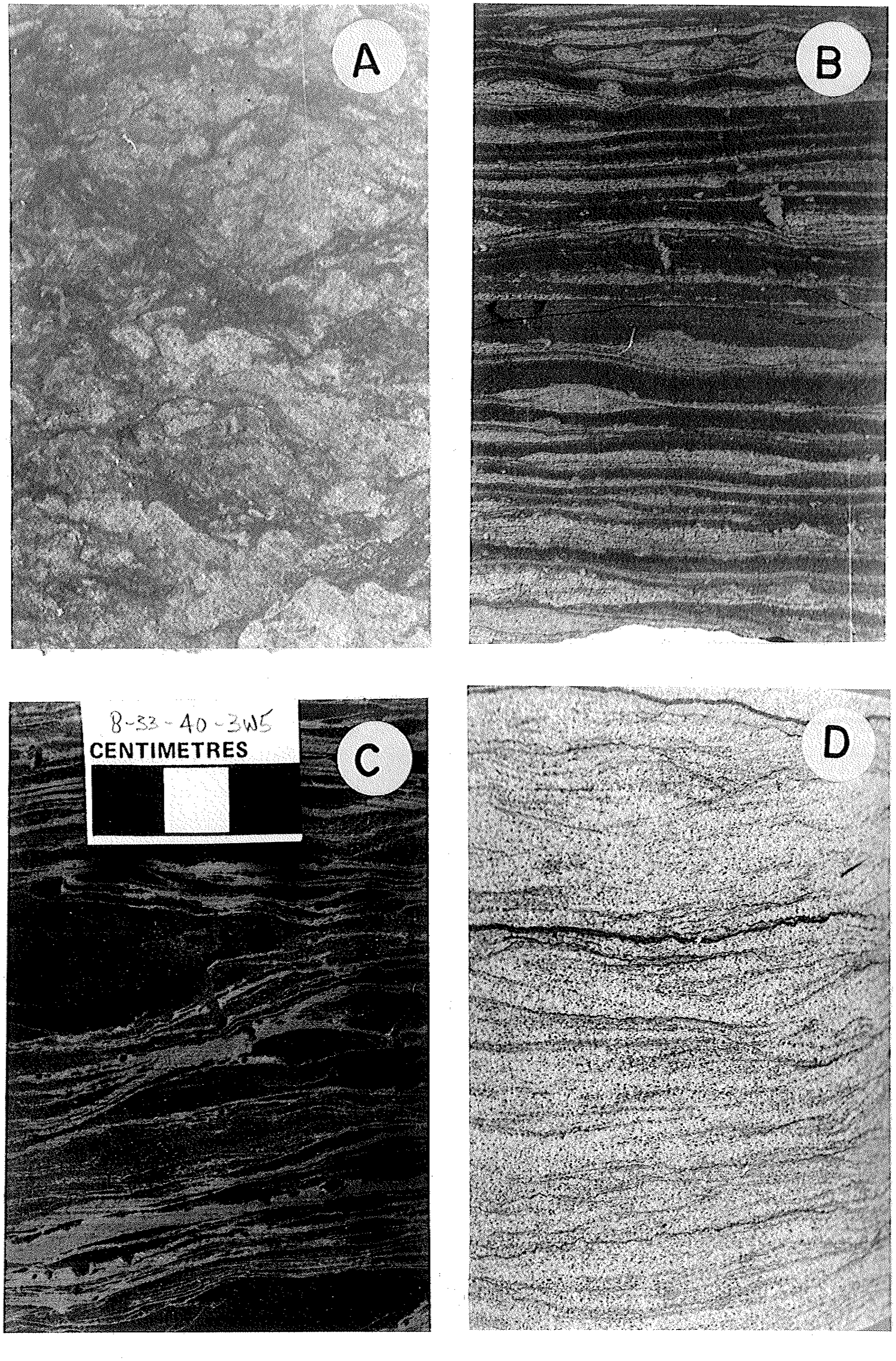
Figure 10 Core photos of representative Jurassic lithofacies (all photos same scale).

(A) Core photo of highly bioturbated argillaceous sandstone (Facies J-4). Note absence of preserved physical sedimentary structures or recognizable burrows (Rock Creek Member, Fernie Formation, 7-11-49-10W5, 2212m).

(B) Core photo of dark ribbon facies (Facies J-2B) showing abundant wave ripples, synaerisis cracks and rare <u>Planolites</u> burrows (Upper Fernie Member, Fernie Formation, 6-13-49-11W5, 2243m).

(C) Core photo of light ribbon facies (Facies J-2A) showing distinctive tan-light grey muds interbedded with ripples, non-bioturbated sandstone (Upper Fernie Member, Fernie Formation, 8-33-40-3W5, 2129m)

(D) Core photo of current-ripples, non-bioturbated sandstone (Facies J3A) Fernie Member, Fernie Formation, 4-36-40-8W5, 2580m


A
B
8-33-40-3W5
CENTIMETRES
C
D

restricted to shallow marine shale of indeterminate (Jurassic-Early Cretaceous) age (Table 2). The interpreted age of most samples of this facies, based on palynology and dinoflagellate content, ranged from Middle to Late Jurassic although several of the samples contained long-ranging species of indeterminate (Jurassic-Cretaceous) age (Table 2).

The J-2C sub-facies consists of highly bioturbated sandy mudstones which are restricted to the Rock Creek Member. The extensive bioturbation has obscured any physical sedimentary structures and no macrofossils were present in this facies although the trace fossils Teichichnus, Planolites and Rosselia were recognized in a few cores (e.g. 10-18-55-12w5). The only sample of this sub-facies which was analyzed for microfossils (SH 88, Table 2) contained a restricted marine dinoflagellate assemblage.

INTERPRETATION

Although the gross lithology of these three sub-facies is similar, they probably represent different depositional environments. Sub-facies J-2A is the most difficult to interpret as it is devoid of any environmentally diagnostic features. The fine-grain size and presence of interbedded wave-rippled sandstones and shales is characteristic of outer shelf deposits where alternating fairweather and storm conditions are represented (Walker 1984). However the general absence of bioturbation, glauconite and microfossils is difficult to reconcile with a shelf environment. The interbedding of light and dark ribbon facies (J2A and J2B) described in some cores (e.g. 4-33-39-5W5) suggests that they represent similar depositional environments which differed only in the degree of oxygenation of the substrate, which would affect the benthic infauna and color of the sediment.

Subfacies J-2B contains many physical sedimentary structures characteristic of shelf deposits (Walker 1984) and the presence of glauconite

(Odim and Matter 1981) and marine microfossils (Table 2) supports this interpretation. The low-density, low-diversity bioturbation may reflect restricted marine conditions (Ekdale et al.1984) and this is further supported by the rare occurrence of synaeresis cracks which commonly record salinity fluctuations in a standing body of water (Plummer and Gostin 1981). The ubiquitous wave ripple lamination probably records frequent storm wave activity whereas the current ripple lamination may record storm ebb, tidal or geostrophic currents in a shelf setting (Walker 1984).

The highly bioturbated sandy mudstone (subfacies J-2C) was probably deposited in a marine setting but lack of diagnostic criteria precludes a more detailed interpretation. The association of this facies with J-4 facies in the Rock Creek is consistent with a open-marine shelf interpretation proposed by Marion (1984).

(iii) J-3 FACIES, SANDSTONE WITH LESS THAN 10% SHALE

The J-3 facies consists of clean (non-argillaceous) fine-grained, highly quartzose sandstones containing less than 10 % interbedded shale laminae. This facies is sub-divided into 4 sub-facies on the basis of grain size and the presence or absence of various sedimentary structures. Subfacies J3A is very fine to fine-grained and contains abundant current ripple lamination (Fig. 10D). Sub-facies J3B is fine to medium-grained and trough-cross stratified whereas subfacies J3C is very fine to fine-grained, structureless and devoid of bedding. Subfacies J3D is also very fine to fine-grained but contains abundant parallel and low angle convergent laminations.

Facies J-3 sandstones are typically non-bioturbated and are restricted to the Upper Fernie interval. This facies often contains angular mudclasts, either in discrete layers or scattered randomly throughout the unit.Stylolite partings are common in more highly indurated cores of this facies (e.g.,8-30-50-13w5).

INTERPRETATION

The clean (non-argillaceous) texture and local presence of upper flow regime bedforms (e.g. parallel lamination) in the J-3 sandstones is indicative of high energy conditions at the site of deposition (Harms et al. 1975). However, not all examples of facies J-3 sandstones are found in the same stratigraphic context and thus they presumably do not all represent the same depositional environment.

In several cores, facies J-3 sandstones cap coarsening-upward sequences composed of restricted marine (J2B,J2A) shales (e.g. 4-33-39-5W5, 10-24-54-13W5), and these are probably storm and wave influenced offshore bar deposits, analagous to those by Brenner and Davies (1974) and Hayes (1983). No evidence of subaerial exposure was noted at the top of the sequences and they do not appear to represent emergent regressive marine shoreline-delta deposits. The paucity of bioturbation is difficult to reconcile with a marine interpretation but this may result from difficulties in recognizing burrow forms in cores of very clean, structureless highly indurated sandstones.

In several cores (e.g. 10-29-29-11W5, 10-28-40-3W5) the clean quartzose sandstones comprise the basal part of thick (10-20m) fining-upward sequences. In these cores, the sandstones have a sharp,scoured base and grade upwards into light ribbon facies (sub-facies J2A). These sequences are superficially similar to Holocene transgressive barrier island sandstones (Reinson 1984) although the absence of bioturbation or marine microfossils in the overlying muddy strata is enigmatic. An alternative interpretation was proposed by Hopkins (1981) who studied the deeply incised channel-form Jurassic sandstones in the Medicine River field (TWP39 R3W5) in the southern part of the study area. He reported fluvial, aeolian andshallowmarine facies within the deeply incised channels and suggested that the fining-upward sandstones could be interpreted as a valley-fill deposit, formed by progradation of a river into a standing body of water. Additional work is required to resolve the age relationships and geometry of the Jurassic sandstones before more detailed environmental interpretations can be proposed.

(iv) J-4 FACIES HIGHLY BIOTURBATED ARGILLACEOUS SANDSTONE

This facies consists of highly bioturbated, argillaceous quartzose sandstone which retains few, if any, primary sedimentary structures (Fig.10A). Generally, the extensive bioturbation has completely churned the sediment such that no trace fossils could be recognized although in some cores (e.g. 6-14-46-10W5) a diverse suite of trace fossils,including _Teichichnus, Terebellina, Paleophycus, Chondrites_ and _Cylindrichnus_ were recognized. This facies is confined to the Rock Creek Member of the Fernie Formation.

INTERPRETATION

The high density-high diversity bioturbation which characterizes the J-4 sandstones of the Rock Creek Member is similar to the _Cruziana_-ichnofacies which is common in open marine shelf settings (Frey and Pemberton 1984). The absence of diagnostic sedimentary structures precludes a more detailed interpretation. The coarsening-upward sequence described in the Rock Creek in other areas (Stronach 1984) is not apparent in the study area as the basal contact with the underlying Poker Chip (e.g. 11-25-54-12W5) is very abrupt and probably represents an unconformity.

(v) J-5 SILICIFIED ARGILLACEOUS CARBONATES

This facies consists of tan to light grey-colored argillaceous lime and dolomite mudstones and chert. This unit was only observed in a few cores (e.g.

6-18-54-7W5) and is confined to the Nordegg Member. In general, the unit is fractured and extensive diagenetic mottling, silicification and extensive pyrite replacement has destroyed most primary sedimentary structures. Sponge spicules and crinoid fragments were reported in the 6-18-54-7W5 core but no other trace or body fossils were recognized.

INTERPRETATION

The light coloration and presence of crinoids and sponge spicules in carbonates of the Nordegg Member are indicative of deposition in a shallow subtidal marine environment. Intense diagenetic alteration has obscured the depositional fabric and prevented a more detailed environmental interpretation.

(vi) J-6 Pyritized regolith

The Jurassic strata in western Alberta contain several unconformities and each of these is marked by some type of regolith or exposure surface. The Nordegg-Poker Chip contact was only examined in one core (e.g. 6-18-54-7W5) and is represented by a 3 meter-thick, silicified, chert-carbonate breccia. This breccia-regolith facies grades downwards into unaltered lime mudstones which are dissected by vertical fractures infilled with green sandy shale.

The Rock Creek-Poker Chip contact was only observed in one of the cores studied in this report (i.e. 1-25-54-12W5) and it is abrupt and marked by a thin shale clast breccia. The contact of the Rock Creek sandstone with the overlying Upper Fernie interval was examined in several cores (e.g. 5-34-48-12w5) and in all instances, the sandstone is capped by a meter-thick silicified, pyritized alteration zone which probably represents some type of paleosol profile.

A fourth Jurassic exposure surface is recognized the Upper Fernie interval in the 10-18-55-12W5 core. This 1.0 meter-thick paleosol is developed immediately above the reservoir sandstone and consists of a bright orange-green mudstone which has been replaced with siderite, silica and hematite.

In general, the Jurassic-Cretaceous contact is knife sharp and is not marked by a paleosol. However, in one core (i.e., 6-18-54-7W5) the upper 2 m of the subcropping Poker Chip shale are intensely fractured and pyritized.

INTERPRETATION

The differences in the thickness, diagenetic textures and mineralogy in each of the five Jurassic-age exposure surfaces identified is probably a function of the subcropping bedrock lithology, duration of exposure and nature and intensity of weathering processes (Retallack 1986). In this study they were not studied in sufficient detail to make any climatic or environmental interpretations.

(B) EARLY CRETACEOUS DEPOSITIONAL FACIES

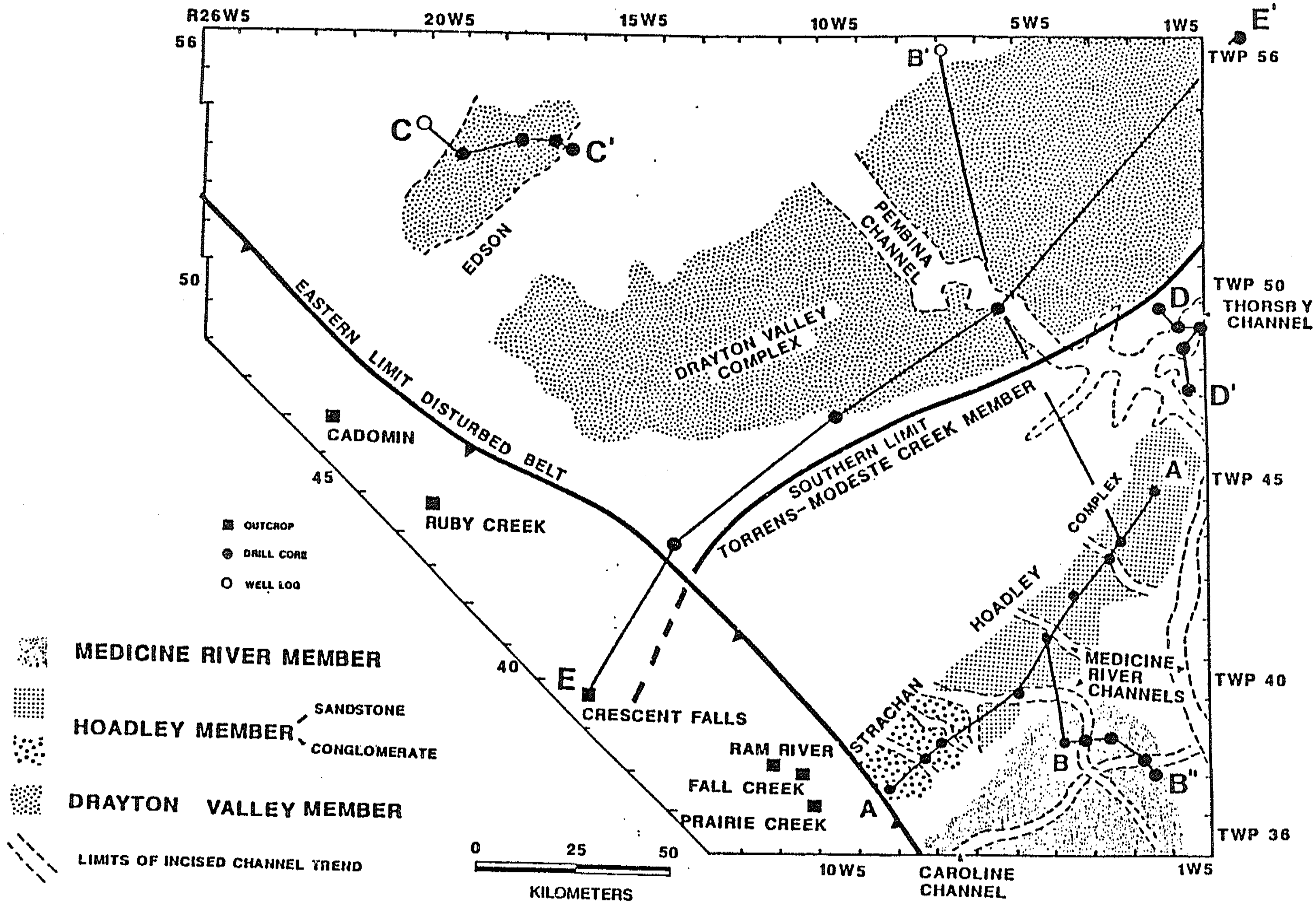
Nine depositional facies were recognized in cores and outcrops of the Mannville-Blairmore strata examined in this study. These nine depositional facies were grouped into two facies associations or "groups of facies which occur together and which are considered to be genetically related" (Reading 1986 p.5). Each facies was divided into several sub-facies and the salient characteristics of, and interpretations proposed for, each of these facies is outlined in Tables 3 and 4.

When this facies data was integrated with gross interval or net clean sandstone isopach maps, the geometry of the sandstone bodies could also be determined. An overview of the geometry and diagnostic characteristics of the facies comprising each association will be presented in the following section. The chapter will close with a detailed discussion and interpretation of each depositional facies recognized in the Early Cretaceous Blairmore, Luscar and Mannville strata examined in this thesis.

(i) OVERVIEW OF FACIES ASSOCIATIONS

The first facies group, interpreted as a marine association, consists of wave-rippled, bioturbated sandstones and shales, and thick hummocky cross-stratified, parallel-laminated and trough cross-stratified sandstones. This association comprises most of the Glauconite Formation in the subsurface and the Moosebar Formation in the Foothills as well as a small part of the upper Ellerslie in the northern part of the study area. Sandstones and shales of this association are typically organized into coarsening and thickening-upward successions which could be readily correlated across the study area. On gamma ray logs, these coarsening-upward sequences exhibited a cleaning-upward profile and the sandstones at the top of the sequence typically exhibit an elongate bar or sheet-like geometry. Four thick (2-25m) sheet-like marine sandstones were identified in the Glauconite Formation in the study area and the approximate areal extent of each is shown in Fig. 11. These sandstones were informally termed the Medicine River, Hoadley, Drayton Valley and Modeste Creek sandstones and their stratigraphic relationship will be discussed in Chapter 6.

The second facies group, interpreted as a brackish to non-marine association, consists of rooted carbonaceous mudstones, weakly bioturbated mudstone with abundant synaeresis cracks, and thick, cross-stratified and/or structureless medium-grained sandstones. This association comprises most of the Gladstone-Ellerslie interval in the study area and, in the Glauconite Formation, is confined to a series of deep (10-40m), narrow (1-5km) channel trends which are outlined in Fig. 11. These channels were difficult to map using gamma ray logs as they can be filled with either sandstone or mudstone and are readily identified only where the lithology of the fill contrasts with that of the enclosing strata. The channels typically exhibit a blocky or



(11) Map showing distribution of marine sandstones and incised channel trends in the Glauconite Formation and location of cross-sections constructed in this thesis.

FACIES		DESCRIPTIONS	INTERPRETATIONS
(1) Shale (< 20% siltstone/sandstone) laminae	1 A	Thinly laminated, non bioclastic, black shale	Offshore marine
	1 B	Highly bioclastic limy shale, 10-80% bioclastic hash, dominantly pelecypods, ostracods, minor gastropods	
	1C	Crudely bedded, sideritic, black shale	
(2) Interbedded sandstones and mudstone	2 A	Thinly laminated, abundant normal grading.	Outer shelf, below storm wave base.
	2 B	Thinly laminated, abundant wave rippling. minor grading	Shelf, above storm wave base
	2 C	Thin to thick bedded, wave rippling & hummocky cross stratification common.	
(3) Bioturbated argillaceous sandstone	3	Highly bioturbated argillaceous sandstone	Shallow marine (undifferentiated)
(4) Clean sandstone (< 10% shale laminae)	4 A	Curviplanar laminated sandstone, probably hummocky/swaley stratification	Lower Shoreface.
	4 B	Parallel and low angle convergent planar lamination,	Foreshore (beach)
	4 D	Highly bioturbated, non argillaceous	Shoreface?
	4 E	Massive, structureless, non bioturbated	Shoreface ?
	4 F	Highly carbonaceous, bioturbated, crudely stratified	Distributary channel
(5) Conglomerate	5 A	Clast supported, no matrix	Foreshore (beach)
	5 B	Clast-supported, sandy matrix	Shoreface

TABLE 3 Description and interpretations of open marine lithofacies, Early Cretaceous, West-Central Alberta.

FACIES		DESCRIPTIONS	INTERPRETATIONS
(6) Clean mudstones (<10% sandstone)		Black-dark grey, massive-crudely bedded, sideritic, traces ostracods,	Clay plug in abandoned reaches of non-marine-estuarine meandering channels
(7) Interbedded sandstones and mudstone	7 A	Carbonaceous, rooted, current ripples, non bioturbated overall,	Emergent overbank, bayfill, lagoonal
	7 B	Weakly bioturbated, non rooted, confined to incised channels in Glauconite Fm,	Subaqueous, brackish (estuarine) channel-fill
	7 C	Weakly bioturbated, abundant synaerisis cracks, soft sediment deformation structures, no roots	Subaqueous, brackish (bayfill-estuarine) fluctuating salinities common
	7 D	Light grey-green, bleached, rooted, sandy mudstones	Paleosol horizon
	7 E	Highly bioturbated, limy, argillaceous sandstone prominant mud-lined skolithos burrows.	Marine-brackish, subaqueous, high energy shoal
(8) Clean sandstone (<10% mudstone interbeds)	8 A	Massive, structureless, minor parallel and low angle convergent laminations.	Incised channel-fill sandstones typically deposited near base of aggrading channels. Absence of bioturbation suggests non marine overall but rare tidal couplets indicate local tidal influence in some cores.
	8 B	Trough cross-stratified, minor tidal couplets foresets, non bioturbated.	
	8 C	Planar tabular cross stratified, poorly sorted, carbonaceous, non bioturbated.	
	8 D	Current ripple laminated, rare flaser bedding, weak non bioturbated.	
	8 E	Pebbly sandstone and conglomerate, sandy matrix,	
	8 F	Clay pebble breccia, sandy matrix containing very angular sideritized mudclasts in sand matrix	Channel lag, typically restricted to base of incised channels
(9) Coals and carbonaceous shale	9 A	Clean coal, negligible interbedded clastics.	Raised coastal plain swamp deposit.
	9 B	Highly carbonacous shale, rooted, non bioturbated.	Non-marine overbank, estuarine salt marsh-lagoonal, bayfill, backswam.

TABLE 4 Description and interpretation of restricted -non marine lithofacies, Lower Cretaceous, West-Central Alberta.

fining-upward profile on gamma-ray logs and the base of each channel is marked by a thick clay pebble (intraclast) breccia. The core facies and isopach data are integrated with detailed geophysical log sections to determine the age of the channels, relative to regional marker beds (e.g. coals or transgressive shales) in the surrounding strata. In all cases, the channels are incised down into, and are therefore younger than, the surrounding strata. A complete discussion of the origin and relative age of these incised channels will be presented in chapter 6.

(ii) OPEN MARINE ASSOCIATION

This group was subdivided into 5 facies on the basis of lithology and the individual facies were further subdivided on the basis of textures and types of sedimentary structures which were dominant within any core or outcrop.

FACIES 1 SHALE (<20% SANDSTONE/SILTSTONE LAMINAE)

This facies consists of dark grey to black shale and mudstone which contains negligible (less than 20%) sandstone and siltstone laminae. These shales comprise most of the Glauconite and Moosebar Formations throughout the study area and a small part of the Ellerslie interval in the northern part of the study area.

Subfacies 1A consists of thinly laminated, non-fossiliferous shale which typically contain up to 20% thin (0.5-5.0 mm) silt laminae which are not disrupted by bioturbation. The only subsurface sample of this facies which was processed for microfossils (i.e. SH-1, Table 5) yielded a sparse assemblage not diagnostic of any environment whereas the outcrop sample (i.e., SH-111, Table 6) yielded a diverse marine foraminiferal assemblage.

Sample #	Location	Facies	Strat. Unit	Foraminiferal Assemblage Interpretation	Palynology/Dinoflagellate Interpretation
SH-14	Gladstone Creek	1A	CM	NR	Marginal Marine
SH-15	Crescent Falls	6	GF (GCM)	NR	NR
SH-107	Crescent Falls	1B	LM	Freshwater - Sl. brackish Early Cretaceous, late Aptian - Lower Albian	NA
SH-110	Cadomin	1B	LM	Freshwater - brackish Early Cretaceous, Late Aptian - Lower Albian	NA
SH - 111	Grande Cache	1A	UM	Marine normal salinity, mid shelf Early Cretaceous, Late Early Albian	NA NA
SH - 113	Ruby Creek	1B	LM	Freshwater - brackish Early Cretaceous, Late Aptian - Early Albian	NA
SH - 116	Fall Creek	1B	LM	Freshwater - brackish Early Cretaceous, Late Aptian - Lower Albian	NA NA

Table 5 - Summary of micropaleontology interpretations, outcrop samples, Cretaceous shales in west central Alberta

NA - not analyzed
LM - Lower Moosebar
GF - Gates Formation
(GCM) - Grand Cache Member
NR - no recovery
CM - Calcareous Member
UM - Upper Moosebar

SAMPLE # LOCATION	FACIES*	STRATIGRAPHIC UNIT**	MICROPALEONTOLOGY ENVIRONMENT/AGE	PALYNOLOGY ENVIRONMENT/AGE
SH-1 13-17-44-2W5, 1909M	1A	UMU	NR	Continental - Marg. Marine L. Cret. (Barremian or Younger)
SH-3 6-15-56-27W4, 3845'	2BC	ELL	Fresh - Brackish Interminate Age	Marg. Marine L. Cret
SH-7 4-33-39-5W5, 2315m	7C	ELL	Fresh - Brackish L. Cret. (Aptian - L. Albian)	Less Marine Than #8, #9 Prob. Mid. Albian or Younger
SH-8 4-33-39-5W5, 2306m	1B,2AB	OST	Brackish - Marine Interminate Age	Marginal Marine Mid. Albian or Younger
SH-9 4-33-39-5W5, 2311m	7B	ELL	NR	Marginal Marine Mid. Albian or Younger
SH-11 14-23-48-2W5, 1588m	6A	GL(CH)	NR	Continental L. Cret (Barremian or Younger)
SH-12 14-23-48-2W5, 1598m	2AB	G	Marine - Prob. Inner Shelf L. Cret. (E. Albian)	Marine L. Cret
SH-18 2-19-39-4W5, 7274	2AB	G	Indeterminate, Marine poss. brachish	NA
SH-19 10-19-40-2W5, 6727	2AB	G	NR	NA
SH-20 14-4-40-5W5, 2287m	6A	G(CH)	NR	NA
SH-35 16-21-44-4W5, 2011m	1C	G	NR	NA
SH-54 8-5-49-1W5, 1506m	7B	G	Possibly Marine	NA
SH-101 6-18-54-7W5, 1622m	1A,2AB	G	NR	NA
SH-114 6-2-50-6W5, 5655'	2AD	G	NR	NA
SH-115 6-2-50-6W5, 5564'	2D	G	Marine, Shallow Shelf Early Cretaceous, Prob. Albian	NA

Table 6: Summary of Age/Environmental Interpretations for Early Cretaceous Shales, West Central Alberta (Subsurface Core Samples)

* *See Tables 3 & 4 For Facies Description*

** *UMU - Upper Manville Undifferentiated, Ell - Ellerslie, G - Glauconite, G (CH) - Glauconite Channel Fill shales, OST - Ostracode*

NR - No Recovery NA - Not Analyzed

Subfacies 1B is a black shale which contains abundant (10-80%) bioclastic detritus (ostracodes, disarticulated pelecypods and high-spired gastropods) either "floating" within the mud matrix (Fig. 12A) or concentrated in thin sharp-based laminae throughout the interval (Fig. 12B). This subfacies contains rare (less than 10%) sharp-based, normally graded and wave-rippled sandstone/siltstone laminae and may be weakly bioturbated. Five samples of this facies were processed for microfossils (i.e., SH-107, 110, 113, 116, Table 5 and SH-8, Table 6) and all yielded a freshwater to brackish (restricted marine) ostracode assemblage. Only one sample (SH-8, Table 6) was processed for palynology and this contained a diverse dinoflagellate assemblage which was interpreted as marginal marine (Table 6). This facies is characteristic of the Ostracode Member (basal Glauconite Formation) in the subsurface (e.g., 6-18-54-7W5) and the Lower Moosebar of the Foothills.

Subfacies 1C is a dark brown to black shale which is thick-bedded, non to weakly bioturbated, non-fossiliferous, and contains abundant sideritic concretionary horizons. The single sample of this facies processed for microfossils was barren (SH-35, Table 6). This facies is restricted to an important marker horizon in the Glauconite Formation (B-marker shale) in the central part of the study area (see Chapter 6).

INTERPRETATION

The fine-grain size and widespread distribution of these shales and mudstones indicate that they were deposited in a large standing body of water. McLean and Wall (1981) cited the different microfossil assemblages as evidence that salinity levels fluctuated in the Early Albian Moosebar Sea. They noted that brackish to freshwater microfossil assemblages were dominant in the lower part of the Moosebar, particularly in the southern part of the study area, and that open-marine assemblages were dominant in the upper part of the

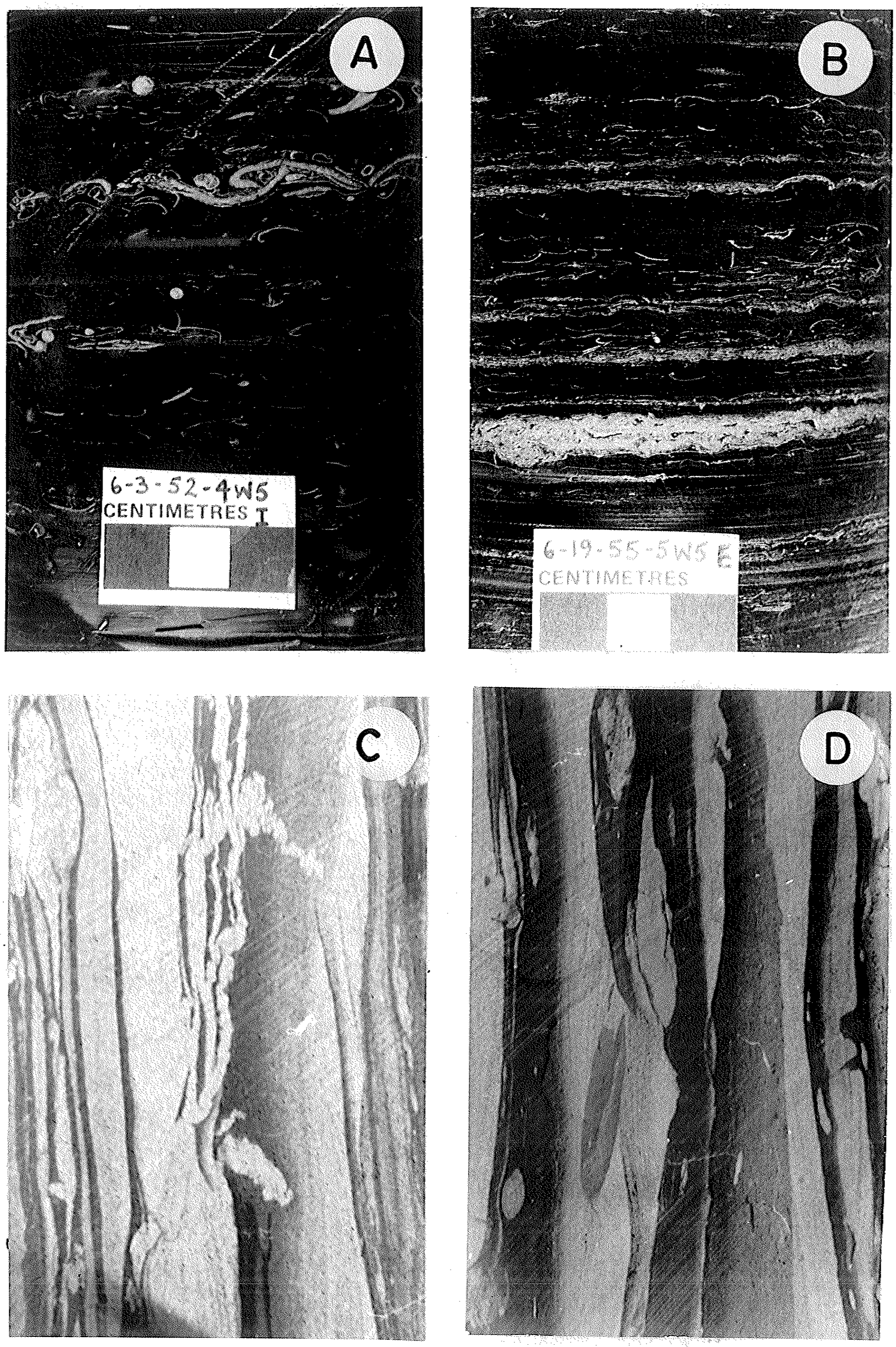
Figure 12 Core Photos of mudstone and shale facies, Glauconite and Ellerslie Formations.

(A) Core photo of black shale (Facies 1B) containing abundant disarticulated bioclastic material including pelecypods, gastropods, and ostracodes floating in mud matrix (Ostracode Member, Glauconite Formation, 6-3-52-4W5, 1497m).

(B) Core photo of black shale containing abundant sharp-based bioclastic laminae (Faces 1B) (Ostracode Member, Glauconite Formation, 6-19-55-5W5, 1441m).

(C) Core photo showing interbedded sandstone and shale (Facies 2B) showing normally graded beds, wave ripples and synaerisis cracks (Ostracode Member, Glauconite Formation, 7-6-47-10W5, 2442m). Field of view 8 cm.

(D) Core photo of interbedded sandstone and shale (Facies 2B) showing abundant normally graded, weakly bioturbated sandstone laminae and distinct absence of wave ripples (Ostracode Member, Glauconite Formation, 6-30-56-3W5, 1233m). Field of view 6 cm.


A
6-3-52-4W5
CENTIMETRES
B
6-19-55-5W5
CENTIMETRES
C
D

Moosebar Formation, particularly in the northern part of the study area. They suggested that these salinity variations resulted from restricted circulation between the Moosebar embayment (Fig. 6B) and the main ocean mass to the north.

The non-bioturbated, organic-rich black shales of subfacies 1A may have been deposited under anaerobic or dysaerobic conditions, possibly below an oxygen minimum (Stronach 1984). The bioclastic shales of subfacies 1B are more difficult to interpret because it is not clear if the benthic infauna are in-situ or transported. Some of the larger fossil fragments "floating" in the mud matrix are possibly in growth position and this would clearly indicate an aerobic substrate. The disarticulated shell hash in the sharp-based laminae was probably resedimented, or at least reworked, by storm activity but the ultimate source of the bioclastic material is problematical. The origin of the siderite horizons in subfacies 1C probably reflects rapid deposition of these shales in a restricted basin with limited circulation. Gautier (1982) reported that siderite is precipitated during very early diagenesis of rapidly deposited, organic-rich shales . Siderite forms when organic matter is left in the sediment after aerobic and sulphate-reducing bacteria have been eliminated by depletion of dissolved oxygen and sulphate in the porewater during burial.

FACIES 2 INTERBEDDED SANDSTONE, SILTSTONE AND MUDSTONE

This facies consists of shale or mudstone interbedded with thin, sharp-based sandstones, and totally bioturbated sandy mudstones. Synaeresis cracks and a low density-low diversity trace fossil assemblage (Fig. 12C) comprised of <u>Planolites</u>, <u>Chondrites</u> and <u>Teichichnus</u> is characteristic of this facies. Eight shale samples from this facies were processed for microfossils (Table 6) and the interpreted environment ranged fron freshwater to brackish (SH-3, 8) to open-marine (SH-12, 115). This facies is developed in the Glauconite, Ellerslie and Moosebar Formations and typically comprises the middle portions of coarsening-upward sequences, above Facies 1 shales and below clean sandstones of Facies 3. This facies is divided into several subfacies, based on the proportion and thickness of the sandstone-siltstone laminae, and the type and abundance of sedimentary structures present.

Subfacies 2A is thinly bedded and contains abundant normally graded sandstone and siltstone laminae (Fig. 12D). Individual beds range from 0.5 to 5.0 cm in thickness and comprise 25-50% of the core interval. Subfacies 2B contains abundant wave-rippled sandstone laminae and the individual laminae are 1-10 cm in thickness, comprise 25-50% of the interval and typically have a sharp top and base (Fig. 12C). Subfacies 2C contains a higher proportion (50-75%) of thicker (5-50 cm) sandstone beds and contains low angle curviplanar convergent lamination interpreted as hummocky cross-stratification. Subfacies 2D consists of totally bioturbated sandy mudstone which retains little or no sedimentary structures. In many cores, these four sub-facies are intimately interbedded, suggesting that they were deposited in a similar depositional environment.

INTERPRETATION

The presence of coarser-grained sediments interbedded with shales appears to record episodic high energy (storm) events in a shallow marine basin in which muds accumulated under fairweather conditions (Walker 1984). The low-diversity-low density bioturbation and presence of synaerisis cracks is atypical of shelf sediments and may reflect the restricted to brackish nature of Early Albian Moosebar Sea, as described above. A thorough discussion of the processes which are capable of transporting and reworking sediment in shallow marine basins is presented in Walker (1984) and some of the important concepts will be highlighted.

Shallow marine sedimentation is influenced by storm, tidal, and wave processes and water depth is the principal factor determining which of these processes are dominant in any given setting. Walker (1984) employs the terms fairweather and storm wave base to describe the maximum depth at which oscillatory waves can significantly modify and rework the bottom sediment during "normal" and storm conditions respectively. During major storms, coarse sediment is initially moved across the shelf by either some type of offshore-directed density current (Walker 1984) or storm surge ebb flow (Nelson 1982) and will be deposited as a sharp-based, normally graded bed. In relatively deep water (below storm wave base), this bed will not be reworked by storm currents and this "turbidite-like" bed will be preserved. At intermediate depths (between storm and fairweather wave base), storm waves and currents can rework these graded beds, forming oscillatory or combined flow ripples and hummocky cross-stratification (Harms et al. 1975). The hydrodynamics of combined oscillatory and unidirectional flow and the formation of hummocky cross-stratification remain poorly understood, primarily due to problems of modelling these conditions in wave tanks and observing them under natural conditions. However, there exists a general concensus among researchers that hummocky cross-stratification records a storm event in a relatively shallow setting (Duke 1985; Walker 1984).

The preservation of normal grading and general absence of wave ripple lamination in subfacies 2A is probably indicative of deposition below storm wave base. Numerical estimates of water depth are difficult to make as wave base is largely a function of (unknown) paleo-wave energy in the system. However, R.G.Walker (pers. comm.) has suggested minimum water depths of at least 50m for subfacies 2A. The abundance of wave rippling and hummocky cross-stratification, and absence of high angle foresets, in subfacies 2B and 2C would represent shallower conditions, presumably between fairweather and storm wave base. The highly bioturbated sandy mudstones of sub-facies 2C indicate that organisms churned the sediment faster than physical processes such as storm waves could rework them. This may reflect slower sedimentation rates during their deposition although many other environmental factors can influence degree of bioturbation (Frey and Pemberton 1984).

FACIES 3 BIOTURBATED ARGILLACEOUS SANDSTONE

This facies comprises a small proportion of the Mannville-Blairmore strata in the study area and consists of a totally bioturbated, argillaceous, fine-grained sandstone which is devoid of any relict sedimentary structures. These argillaceous sandstones are developed in the Glauconite and Ellerslie Formations in the subsurface and in the Middle Moosebar of the Foothills (e.g. lower twin sandstone, Crescent Falls section, Appendix 3B). In most cases, this facies marks the transition between a shale or interbedded sandstone-shale interval, and a relatively clean sandstone and appears to grade into both the overlying and underlying facies. Trace fossils recognized in this facies include Paleophycus, Cylindrichnus, Rosselia, Terebellina and Macronichnus segregatus.

INTERPRETATION

The association of this facies with open marine muddy strata (Facies 1 and 2) and hummocky cross-stratified, glauconitic sandstones (Facies 4) indicates that this facies was deposited in a shallow, open marine (shelf) setting. The ubiquitous bioturbation clearly indicates that biologic processes dominated over physical sedimentary processes and this apparently reflects optimum conditions for colonization by benthic fauna .

Figure 13 Representative trace fossils in Mannville cores. All cores approximately 10 cm wide.

(A) Core photo showing interbedded sandstone and shale (Facies 7C) containing abundant synaerisis cracks and soft sediment deformation structures and *Planolites* burrows (Ellerslie Formation,4-36-40-8W5, 2568 m)

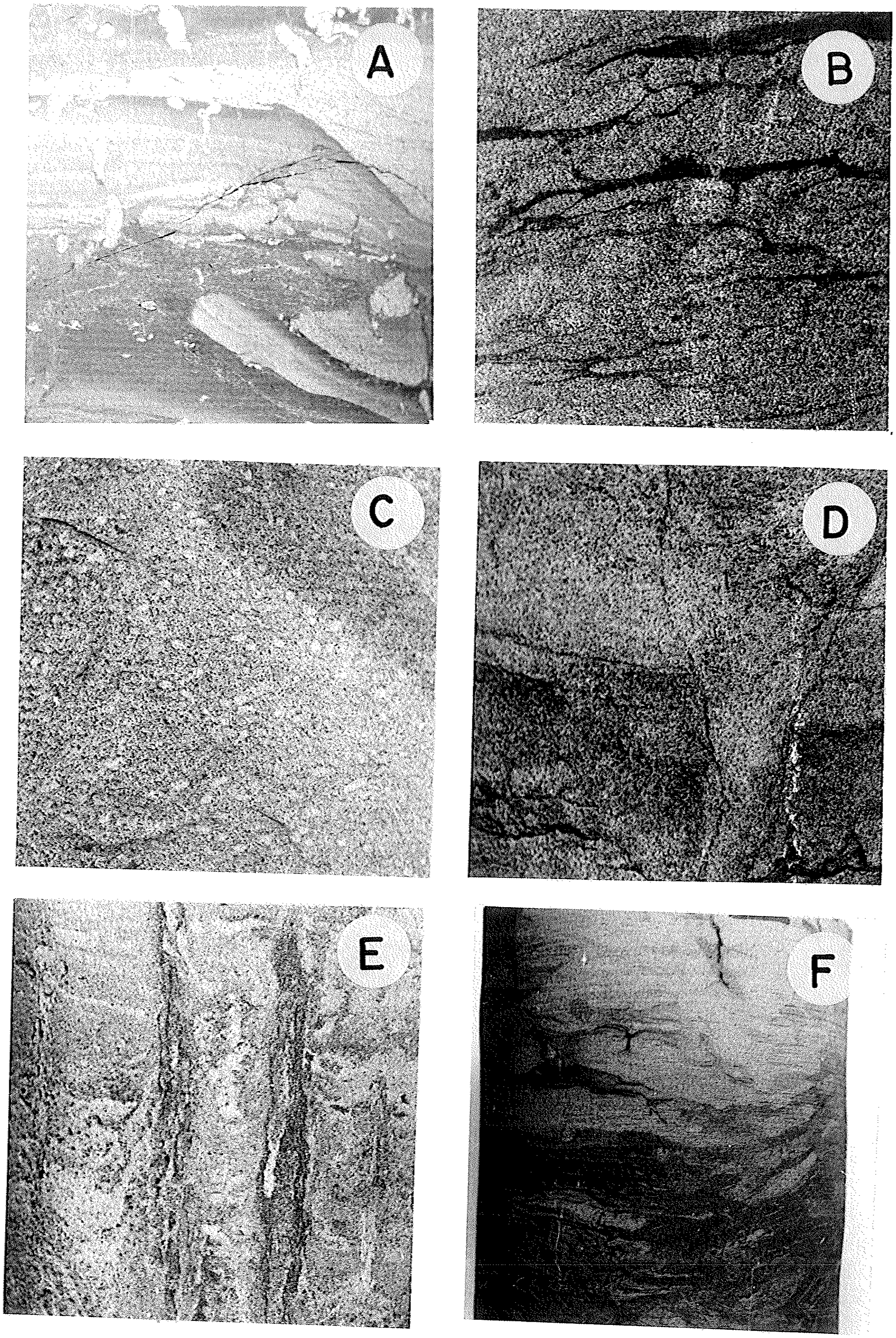
(B) Core photo of *Paleophycus* burrows (Hoadley Member, Glauconite Formation, 2-16-43-4W5, 2033m).

(C) Core photo of *Macronichnus segregatus* burrows (Hoadley Member, Glauconite Formation, 2-16-43-4W5, 2034m).

(D) Core photo of funnel-shaped *Rosselia* burrow (Ellerslie Formation, 6-21-48-16W5, 9597´).

(E) Core photo of mud-lined *Skolithos* burrows (Ellerslie Formation, 6-27-41-3W5, 6970´).

(F) Core photo showing sharp transition between sandstone and shale with abundant soft sediment deformation structures (Facies 7C) and argillaceous rooted sandstone (Facies 7A) (Ellerslie Formation, 6-18-47-6W5, 6745´).


A
B
C
D
E
F

FACIES 4 CLEAN SANDSTONE (LESS THAN 10% INTERBEDDED SHALE)

This facies consists of relatively clean (non-argillaceous), very fine to medium-grained sandstone containing minor (<10%) shale laminations. This facies is typically found at the top of coarsening-upward sequences in the Glauconite and Moosebar Formations but is also present in the Ellerslie interval in the northern (subsurface) part of the study area. This facies has been subdivided into a series of subfacies based on the presence or absence of various sedimentary structures.

Sandstones of subfacies 4A are typically fine to very fine-grained and contain abundant curviplanar parallel and convergent laminations (Fig. 14C). These laminations are interpreted as either hummocky (HCS) or swaley cross-stratification (SCS), as defined by Harms et al (1975) and Leckie and Walker (1982) respectively.

Subfacies 4B sandstones are similar to 4A except the convergent laminae recognized in the cores are planar (Fig. 14A) rather than curviplanar as in subfacies 4A. The sandstones in subfacies 4B are typically coarser-grained and are generally developed above subfacies 4B in any coarsening-upward sequence (e.g., 8-5-41-5W5).

Subfacies 4C typically consists of fine to medium-grained sandstone which contains angle of repose, steepening-upward foresets which exhibit a highly variable orientation in cores (Fig. 14B). These foresets are interpreted as trough-cross stratification and are commonly developed near the top of coarsening upward cycles in the Glauconite Formation, just below a rooted zone (e.g.,10-35-40-7W5).

Subfacies 4D consists of highly bioturbated, non-argillaceous (clean) sandstone (Fig. 14D). This facies is relatively rare and is typically

Figure 14 Core photos of marine sandstone facies, Glauconite Formation. Field of view in all photos approximately 10 cm.

(A) Core photo of clean marine sandstone exhibiting parallel and low angle convergent laminations (Facies 4B) (Hoadley Member, Glauconite Formation, 8-8-41-6W5, 2384m).

(B) Core photo of high angle cross-stratification (probably trough cross-bedding) (Hoadley Member, Glauconite Formation, 10-35-40-7W5, 2463m).

(C) Core photo of hummocky cross-stratified sandstone (Facies 4A). Note abundant curviplanar laminations, low angle truncation surfaces and complete absence of angle of repose foresets (Drayton Valley Member, Glauconite Formation, 6-30-56-3W5, 1236m).

(D) Core photo of highly bioturbated non-argillaceous sandstone (Facies 4D). Note excellent <u>Terebellina</u> and <u>Macronichnus</u> <u>segregatus</u> burrows and absence of preserved physical sedimentary structures (Hoadley Member, Glauconite Formation, 2-16-43-4W5, 2034m).

interbedded with hummocky and swaley cross-stratified sandstones of sub-facies 4A (e.g., 11-26-45-2W5). Trace fossils recognized in this facies includePaleophycus, Rosselia, Macronichnus segregatus, Terebellina, Asterosoma, and Ophiomorpha(Fig. 13A, B and C).

Subfacies 4E consists of massive, structureless sandstones which contain no recognizable physical or organic sedimentary structures. This sub-facies comprises most of the Glauconite sandstones in the Hoadley-Strachan and Drayton Valley trends (Fig. 11) and commonly forms the bulk of the clean sandstone capping these coarsening-upward sequences (e.g.,1-30-43-1W5).

Subfacies 4F consists of dark grey-green colored, highly carbonaceous, crudely bedded, fine to medium-grained sandstone. This facies is only recognized in the Glauconite Formation along the Strachan-Hoadley trend (Fig.11) where it caps a thick coarsening-upward sequence (e.g., 10-22-42-5W5). This sandstone is poorly sorted and and less porous than other clean sandstone facies in the Hoadley trend and appears to have a very erratic distribution.

INTERPRETATION

Sandstones of facies 4 typically comprise the middle and upper parts of coarsening-upward shallow marine sequences. Each subfacies is interpreted differently, depending on the dominant type of sedimentary structures present.

The hummocky cross-stratified sandstones (subfacies 4A) were probably deposited in a storm-influenced shallow marine environment between storm and fairweather wave base (Walker 1984). The sand was presumably stripped from adjacent sandy coastal zones during storms and redeposited in the shallow marine environment where it could have been reworked by storm waves. The absence of high angle cross-stratification in this facies probably indicates that the sand was redeposited below fairweather wave base where the water was too deep to permit fairweather oscillatory waves to rework the sediment (Walker 1984). However, the absence of high angle cross-stratification may also be a consequence of the grain size of subfacies 4A sandstones as there is no stability field for sand waves and dunes in very fine-grained sandstones (Harms et al.1975).

The parallel and low angle convergent laminated sandstones (subfacies 4B) are very similar to beach deposits in wave-dominated environments (Reinson 1984). The lamination would be formed by swash-backwash processes in the foreshore. The frequent development of a rooted zone capping subfacies 4B sandstones supports a foreshore interpretation as many beach sandstones are capped by vegetation (Reinson 1984).

The trough cross-stratified sandstones (subfacies 4C) occasionally found near the top of the coarsening-upward sandstones were probably deposited in an upper shoreface setting where breaking waves caused the migration of megaripples across shoreline-attached bars (Clifton et al.1971).

The bioturbated sandstones of subfacies 4D and the structureless sandstones of subfacies 4E are difficult to interpret as they contain no depth-diagnostic sedimentary structures. The clean (non-argillaceous) texture of these sandstones and their association with hummocky cross-stratified sandstones and conglomerates is indicative of a high energy (probably shoreface) marine environment.

The highly carbonaceous sandstones of subfacies 4F are very similar to distributary channel deposits described in modern deltaic settings which contain large amounts of organic material "comminutated coffee grounds" (Coleman 1981). As this facies is restricted to the Hoadley-Strachan Complex, which is interpreted as a wave-dominated shoreline, the carbonaceous sandstones must have been deposited in a channel system as the organic material would have been winnowed from the sands in the high-energy shoreface or foreshore.

A more detailed discussion of depositional environments represented by these sandstones will be presented in chapter 6.

FACIES 5 CONGLOMERATES

In the extreme southwest corner of the study area (Strachan area), a thin conglomerate is developed at the top of the Glauconite Formation (e.g., 10-22-37-9W5). A similar conglomerate was recognized in the equivalent Middle Moosebar interval in the nearby Tay River outcrop (Appendix 3B). The conglomerate is clast-supported and contains varicolored chert and quartzite pebbles up to 4 cm in maximum dimension. These conglomerates are either well sorted and matrix-free (Fig. 15B, subfacies 5A) or poorly sorted and contain a fine-grained, glauconitic sandy matrix (Fig. 15A, subfacies 5B). The contact with the underlying marine sandstone is sharp (Fig. 15C) although the underlying sandstone may contain several thick (5-30 cm) sharp-based conglomerate beds below this contact. The largest clasts and highest proportion of sandy matrix is found near the base of the conglomerate and the maximum clast size and the proportion of sandy matrix decreases upward. No stratification, imbrication or bioturbation was recognized in the core although low angle (15 degree) foresets, possibly representing lateral accretion surfaces, were recognized in the Tay River outcrop of the Upper Moosebar conglomerate (Fig. 15D). The uppermost part of the Hoadley interval was not cored in the 10-22-37-9W5 well although geophysical logs from this well indicate that it is capped by a thin coal horizon which is correlative with the coal which caps the adjacent Hoadley sandstones (e.g., 7-12-38-9W5). This confirms that these conglomerates are age-equivalent to, and comprise part of, the same wave-dominated shoreline deposit as the Hoadley sandstones.

Thin stringers of glauconitic conglomerate (sub-facies 5B) up to 15 cm in thickness were recognized within the fine-grained sandstone throughout the

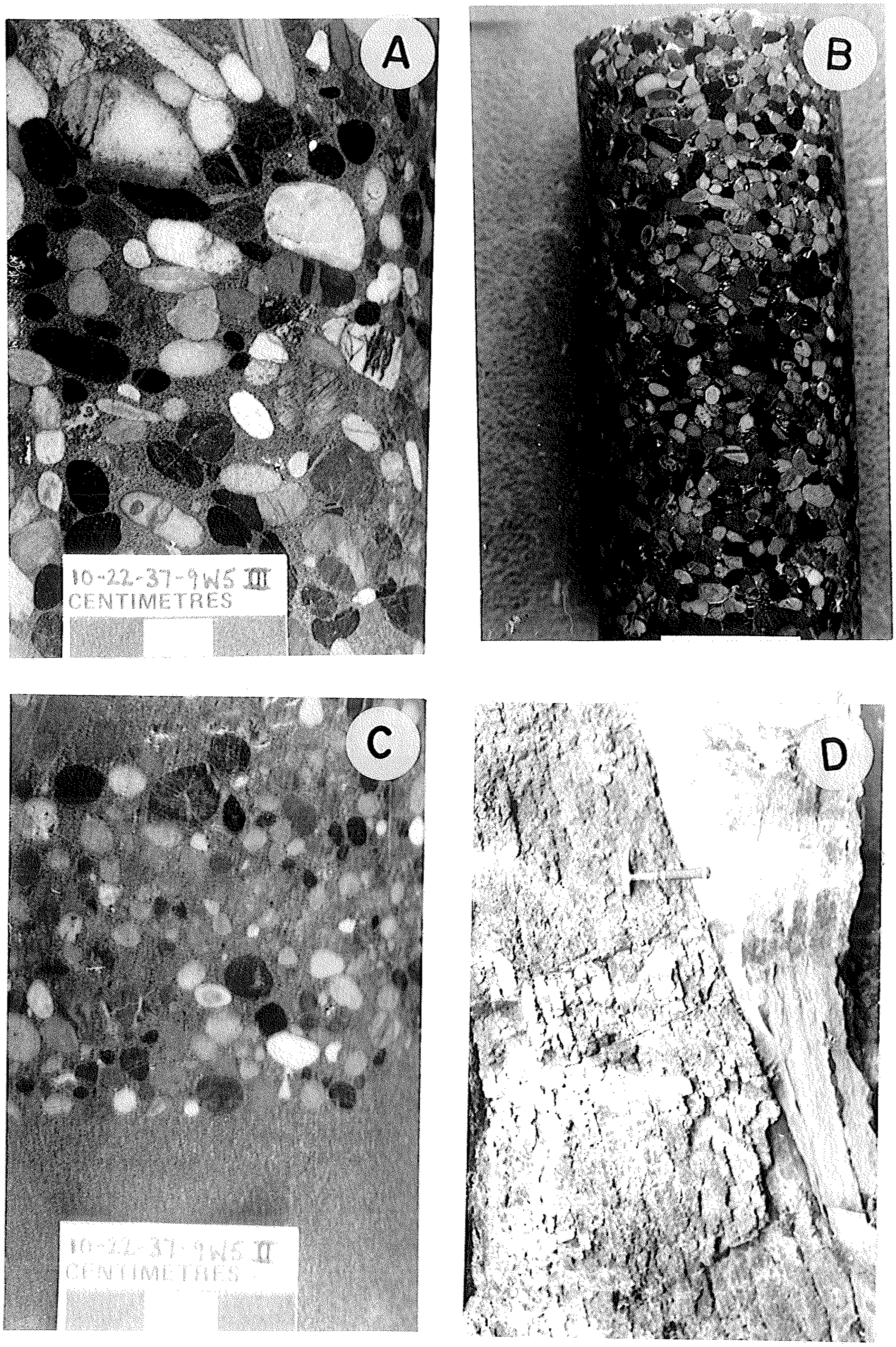
Figure 15 Core and outcrop photos of marine conglomerates, Glauconite Formation and equivalent middle Moosebar interval.

(A) Core photo of clast-supported conglomerate with sandy matrix (Facies 5B) (Hoadley Member, Glauconite Formation, 10-22-37-9W5, 3131m).

(B) Core photo of clast-supported conglomerate without sandy matrix (Facies 5A) (Hoadley Member, Glauconite Formation, 10-22-37-9W5, 3124m). Core width 10 cm.

(C) Core photo showing sharp contact between massive structureless marine sandstone (Facies 4B) and clast-supported conglomerate with sandy matrix (Facies 5B) (Hoadley Member, Glauconite Formation, 10-22-37-9W5, 3132m).

(D) Outcrop photo of clast-supported pebble conglomerate (Facies 5A, B). Note low angle lateral accretion surface in conglomerates above the erosional scour which cuts down into parallel laminated sandstones (middle Moosebar, Tay River section). Field of view approximately 5m.


A
10-22-37-9W5 III
CENTIMETRES
B
C
10-22-37-9W5 II
CENTIMETRES
D

length of the Strachan-Hoadley trend. These thin beds are not randomly distributed within the Hoadley sandstone but appear to mark some type of transgressive lag which caps a lower coarsening-upward sequence within this composite sandstone body (e.g. 6-10-44-3W5).

INTERPRETATION

The stratigraphic equivalence and lateral continuity of the Strachan conglomerates with sandstones in the Hoadley trends confirms that they were also deposited along a wave-dominated coastline. Cant (1984) has interpreted similar conglomerates from Early Cretaceous Fahler Formation of northern Alberta as regressive wave-dominated shoreline deposits. He interpreted the well-sorted, matrix-free conglomerates at the top of the regressive marine sequences as foreshore deposits and the underlying, poorly sorted, sand-rich conglomerate as distributary channel or shoreface deposits. Lack of data precludes a more detailed interpretation for the Strachan conglomerates at this point.

The thin conglomerate in the middle of the marine sandstone comprising the Hoadley-Strachan trend apparently records a transgressive event as the muddy sandstones overlying the conglomerate is a deeper-water facies than clean, well sorted sandstone below the conglomerate. Similar transgressive conglomerates have been described in other Cretaceous marine sequences in the Alberta Basin including the Cardium (Plint et al.1987), Viking (Leckie 1986) and the Chungo Formations (Rosenthal and Walker 1987). A detailed discussion of the origin of these conglomerates this will be presented in the chapter 6.

(iii) BRACKISH TO NON-MARINE FACIES ASSOCIATION

Four depositional facies have been recognized in the brackish to non-marine association and the salient characteristics of each is outlined in Table 4 .

The four facies are defined primarily on the basis of lithology and the various sub-facies are differentiated on the basis of the presence or absence and abundance of roots, trace fossils and sedimentary structures.

FACIES 6 MUDSTONE FACIES (LESS THAN 10% INTERBEDDED SANDSTONE)

This facies consists of mudstones and shales which contain less than 10% admixed sandstone. These mudstones are massive to crudely bedded and contain abundant siderite concretions, carbonaceous laminae and rare (less than 10%) sharp-based, weak to non-bioturbated sandstone laminae. This facies commonly forms laterally discontinuous mud "plugs" within incised channel trends in the Glauconite interval (e.g. Thorsby area, 14-33-48-1W5) and grades laterally across very short distances (less than 2 km) into coarser sandy channel-fill sequences (e.g., 4-34-48-1W5). This facies is notably devoid of any signs of emergence (roots, paleosols etc.) and is typically non-bioturbated. Both samples (SH-11, 20, Table 6) of this facies which were processed for microfossils were barren of foraminifera and one (SH-11) was interpreted as continental on the basis of pollen assemblage and absence of dinoflagellates (Table 6, Appendix 6).

INTERPRETATION

The dark coloration and very fine-grained (muddy) nature of this facies is superficially similar to the open marine mudstones of facies 1. However, the mudstones of facies 6 are clearly restricted to narrow channel trends (discussed in the following chapter) and are associated with non-bioturbated sandstones which are interpreted as fluvial or estuarine valley-fill deposits. The lenticular geometry and sand-free nature of this subfacies is typical of "clay plugs" formed during the avulsion and abandonment of meander loops in a high-sinuosity fluvial system (Walker and Cant 1984). Similar sequences have also been described in the sinuous upper reaches of tidally influenced estuarine systems (Dorjes and Howard 1975). A detailed discussion of the (estuarine versus fluvial) origin of these channels will be presented in chapter 6.

FACIES 7 INTERBEDDED SANDSTONES AND MUDSTONES

Facies 7 consists of interbedded sandstones and mudstones which exhibit very different depositional textures and structures than mixed sandstones and mudstones of facies 2. A meagre ostracode assemblage recovered from one sample of this facies was interpreted as fresh to brackish (Table 6, SH-7) whereas the dinoflagellate-pollen assemblage from this and another sample (SH-9) was interpreted as marginal marine. Sand-filled shrinkage cracks in the muddy sediment have a spindle-form in plan view which is characteristic of synaeresis, rather than desiccation cracks (Plummer and Gostin 1981).These structures probably record episodes of fluctuating salinity in a semi-restricted marine embayment.

Subfacies 7A comprises the bulk of the Ellerslie-Gladstone interval and is also recognized within incised channel trends in the Glauconite Formation. This facies consists of dark grey to black carbonaceous mudstones which contain variable proportions of crudely bedded sandstone containing numerous root traces, synaerisis cracks, current ripples, parallel and convergent lamination, and soft sediment deformation structures (Fig. 13E,F). The thickness of individual sandstone laminae ranges up to 150 cm and no consistent changes in the proportion, thickness or grain size of these sandstones were recognized in this facies.

Sub-facies 7B has a similar lithology to 7A but is devoid of any signs of emergence (e.g., root traces) and has a well-bedded appearance, due to the abundance of weakly bioturbated sandy horizons with diffuse upper and lower contacts (Fig. 16B). This sub-facies was only recognized within incised channels in the Glauconite Formation and is best developed in the Thorsby area (e.g., 14-22-48-2W5).

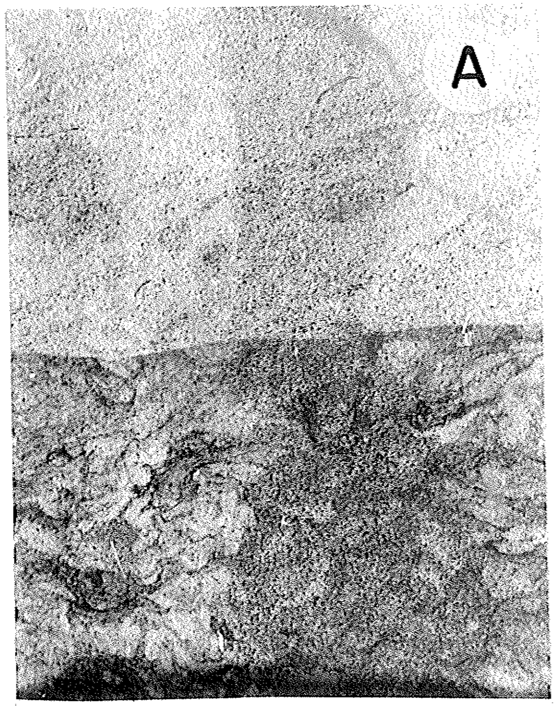
Subfacies 7C also consists of admixed sandstone and mudstone but is non-rooted and bioturbation is generally absent although rare Planolites and Skolithos burrows were observed in a few cores. Soft sediment deformation structures, synaerisis cracks and small scale normal faults were present in many cores and ostracod and pelecypod shells were often observed "floating" in the mud matrix. This subfacies repeatedly exhibits small (meter-scale) coarsening-upward sequences in which bioturbated argillaceous sandstones (subfacies 7D) grades upward into rooted mudstones (subfacies 7A) over very short stratigraphic intervals (Fig. 13E).

Subfacies 7D consists of light grey to tan-colored "bleached" paleosol horizons which are extensively rooted and exhibit abundant pyrite and siderite alteration. These horizons typically exhibit a gradational lower contact and a sharp upper contact. In some cores of the Ellerslie Formation, up to five paleosol horizons were recognized (e.g., 8-24-50-2W5).

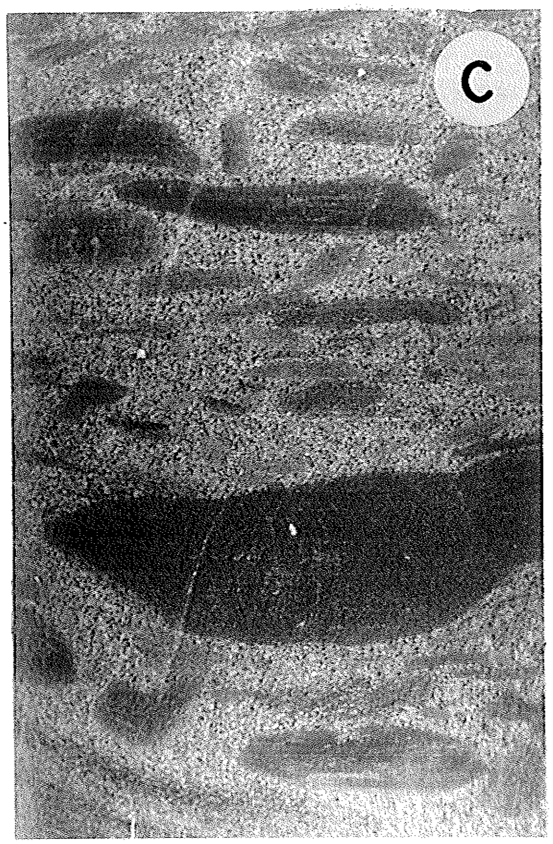
Subfacies 7E consists of extensively bioturbated argillaceous, calcareous sandstone which contains numerous mud-lined Skolithos burrows. This facies is restricted to the Ellerslie Formation and is typically represented by thin (less than 1 m) units which grade into more argillaceous units (e.g. 7-3-48-14W5).

INTERPRETATION

The muddy texture, low density-low diversity trace fossils, abundance of synaeresis cracks and brackish to marginal marine microfossil content are all



8-21-44-4W5 ///



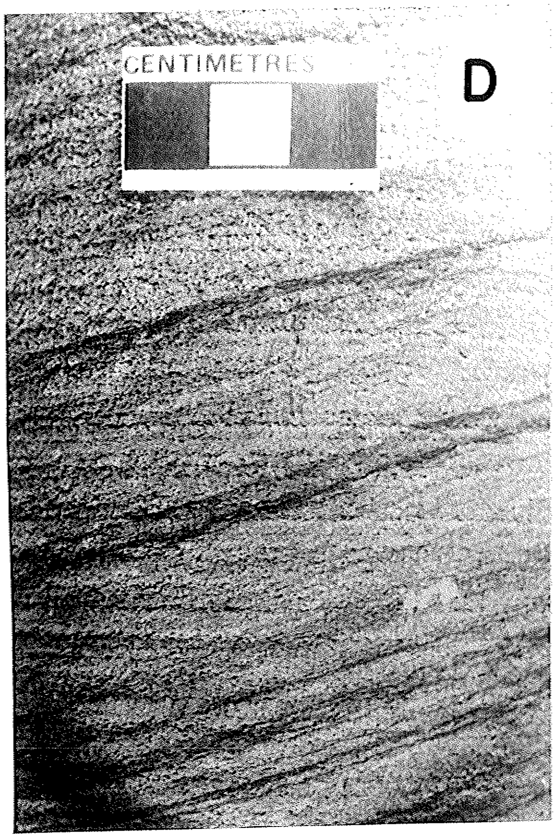


Figure 16 Core photos of restricted-non-marine, facies, Glauconite and Ellerslie Formations. All photos same scale.

(A) Core photo showing sharp contact between bioturbated argillaceous sandstone (Facies 3) and trough cross-stratified sandstone (Facies 8B) (Ellerslie Formation, 8-21-44-4W5,2033m).

(B) Core photo showing weakly bioturbated sandstone/mudstone interbeds (Facies 7B) near top of incised channels in the Pembina area. Note diffuse upper and lower contacts of the sandstone beds and abundant small scale mud-lined Skolithos burrows (Glauconite Formation, 6-1-50-7W5, 1753m).

(C) Core photo showing intraclastic breccia (Facies 8F) typically found at base of incised channels (Glauconite Formation, 16-1-50-1W5, 1400m).

(D) Core photo showing tidal couplets along high angle foresets in channel sandstones dissecting Hoadley bar trend (Glauconite Formation, 10-12-44-2W5, 1781m).

indicative of relatively low energy, restricted marine to non-marine conditions. The presence of mud-lined Skolithos burrows in sub-facies 7E supports at least a limited marine influence as freshwater organism which form Skolithos burrows do not line the shafts with mud (Ratcliffe and Fagerstrom 1980). The dark coloration and intimate interbedding of rooted and non-rooted zones is very similar to poorly drained overbank (backswamp) deposits in an alluvial setting (Retallack 1986) and also to bayfill sequences in river-dominated deltas (Coleman 1981; Elliot 1974).It is difficult to interpret specific depositional environments (i.e. levee, crevasse splays) for the various subfacies because they are intimately interbedded and the lateral relationships of the various subfacies to channel trends could not be established with the existing data base. Only a few long continuous cores are available in the Ellerslie Formation (e.g. 14-31-52-8W5) and these revealed that the lower part of the interval was dominated by highly carbonaceous, rooted (emergent) sediments (subfacies 7A) whereas the upper part of the interval was more highly bioturbated and contained abundant ostracode-bearing shales (subfacies 7C, E), suggesting dominantly subaqueous brackish conditions. This appears to record a gradual marine transgression over a low-lying, low energy coastal plain. The presence of repeated coarsening-upward sequences and alternation of emergent and subaqueous facies in the Ellerlslie was probably the result of recurrent fluctuations in relative sea level.

Sub-facies 7B is distinct from the rest of facies 7A in that it is restricted to the upper portions of incised channel sequences within the Glauconite interval. The ubiquitous low-density, low diversity bioturbation which characterizes this facies is similar to brackish estuarine channel sequences described by Wightmann et al.(1987). This suggests that the incised channel trends may have been inundated by a transgressing sea, at least during the later stages of aggradation. The origin of these incised channels will be discussed in more detail in chapter 6.

FACIES 8 CLEAN (NON-ARGILLACEOUS) CHANNEL SANDSTONES AND CONGLOMERATES

This facies consists of light colored, clean (non-argillaceous), well-sorted, fine to medium-grained sandstones which contain less than 10% mudstone interbeds. This facies is interbedded with restricted to non-marine mudstones (facies 7) in the Ellerslie-Gladstone and Beaver Mines intervals and is confined to deep, narrow incised channels in the Glauconite Formation. This facies was divided into 5 subfacies on the basis of the type of sedimentary structures present and a brief description of each is listed in Table 4.

Subfacies 8A consists of structureless to crudely bedded, well sorted, non-bioturbated sandstone. Rarely, the sandstone exhibits crude parallel to low angle convergent lamination and contains thin shale interbeds. This facies comprises the bulk of sandy channel-fill sequences in most incised channels in the Glauconite Formation (e.g., 7-5-45-2W5).

Subfacies 8B has a similar lithology but contains abundant steepening-upward, angle of repose foresets which exhibit a highly variable orientation across short core intervals. These foresets are interpreted as trough cross-stratification,and were probably formed by unidirectional currents which caused the migration of lower flow regime, sinuous-crested subaqueous sand dunes (Harms et al. 1975).

Subfacies 8C also consists of clean (well sorted), fine to medium-grained sandstone with high angle foresets but the inclination of these foresets is uniform (20-28 degrees) and, across long cored interval, most foresets dip in the same direction. These foresets are interpreted as planar tabular cross-stratification which was probably generated by the migration of straight-crested sand waves under lower flow regime, unidirectional flow conditions (Harms et al.1975). Very commonly, these foresets have a "banded" appearance which results from the concentration of carbonaceous and micaceous material along the foreset bedding planes. In some cores, these carbonaceous laminae form tidal couplets (Visser 1980) in which there exists a rhythmic alternation of sand laminae separated by muddy, carbonaceous intervals (Fig. 16D). This subfacies is generally non-bioturbated although it may contain interbedded weakly bioturbated muddy sandstones (subfacies 7B) in some cores (e.g., 14-3-49-1W5).

Subfacies 8D consists of clean, non-argillaceous, very fine to fine-grained sandstone which contains abundant current ripple laminations and rare flaser interbeds. This facies is relatively rare and was described in the Ellerslie Formation (e.g. 10-14-46-14W5) and within the incised channels in the Thorsby area (e.g. 16-36-48-2W5).

Subfacies 8E consists of clast-supported conglomerates and pebbly sandstones which contain chert and quartz pebbles up to 5 cm in diameter. The conglomerates typically have a sandy matrix, are crudely stratified and exhibit no imbrication. This facies was present in the Ellerslie Formation in one core in the subsurface (e.g. 5-12-50-5W5) and comprised the bulk of the Cadomin Formation in most Foothills outcrops. The conglomerates of this facies are very similar to the marine conglomerates (facies 5) described previously and distinction between these two facies is based primarily on the stratigraphic context of the unit.

Subfacies 8F consists of coarse intraclastic breccia which contains angular pebble, cobble and boulder-sized blocks of shale and mudstone in a poorly sorted carbonaceous sandy matrix (Fig. 16C). No physical or organic sedimentary structures were recognized in the intraclastic breccia facies and the clasts exhibit little or no evidence of rounding or abrasion. This facies commonly forms a lag at the base of incised channels in the Glauconite Formation. In most incised channels, several intraclastic breccia horizons are developed (e.g. 14-22-48-2W5). This facies was also recognized at the base of the Beaver Mines Formation in the Ram River outcrop and at the top of the Luscar interval in the Ruby Creek section (Appendix 3B).

INTERPRETATION

Most of the sedimentary structures and textures in facies 8 sandstones (i.e. trough and planar cross stratification and intraclast breccias) indicate that relatively high energy conditions prevailed during their deposition. However, these structures are not uniquely diagnostic of any environment and the sandstones could represent an incised fluvial system, similar to the modern South Saskatchewan River (Walker and Cant 1984) or a drowned river valley-type estuary, similar to that described by Dorjes and Howard (1975). The presence of weakly bioturbated sandy mudstones (facies 7B) near the top of many fining-upward sequences, and local occurrence of tidal couplets, suggests that a marine influence was present, at least during the later stages of valley aggradation. In most of the incised channels recognized in the study area, the drilling density was insufficient to resolve the geometry of individual sandstone bodies. However, closely spaced drilling in the Thorbsy area revealed that these sandstones exhibited pronounced (10-25 m) thickness variations over very short (<1.0 km) distances. The discontinuous nature of the sandstones, presence of repeated muddy fining-upward sequences,and common occurrence of facies 6A mudstones (abandoned channel clay plugs) suggest that most of the facies 8 sandstone were deposited by some type of meandering channel within an incised valley. The processes which led to the incision and aggradation of these channels will be discussed in chapter 6.

FACIES 9 COAL AND CARBONACEOUS SHALE

Thick sections of coal and carbonaceous shale were observed in cores and outcrops of all the Lower Cretaceous units described in this study. Clean (non-shaly) coals were included in subfacies 9A whereas those with appreciable clastic interbeds were included in subfacies 9B. The coals are typically shiny black in color, well bedded and retain numerous plant impressions on the bedding planes. The petrographic and chemical characteristics of the coal and carbonaceous shales were not investigated in this thesis.

Most of the thick (up to 8 m) clean coal horizons (subfacies 9A) were developed above marine strata. Examples of this association include the Glauconite Coal capping the Hoadley and Medicine River sandstones in the subsurface and the Jewel Seam capping the Torrens Member of the Moosebar Formation in the Foothills (e.g. Cadomin section, Appendix 3B). Another thick coal horizon, informally termed the Medicine River Coal by local oilfield operators, reaches a maximum thickness of 8 m and extends over at least 10000 km^2 in the southern part of the study area. This coal is developed approximately 20 m above the top of the Glauconite Formation and is interbedded with non-marine strata of the upper Mannville (e.g. 13-17-44-2W5). Although this coal is not directly associated with marine strata, it appears to be stratigraphically equivalent to a thin marine shale developed in the upper Mannville in the northern part of the study area (see chapter 6).

In addition to these thick "regional" coal markers, numerous thin discontinuous coals and carbonaceous shales were also described in the largely non-marine Gladstone Formation in the northern and central Foothills and in the basal Ellerslie and Upper Mannville of the Plains.

INTERPRETATION

The carbonaceous strata of facies 9 was clearly deposited in some type of lagoonal or swamp setting, but, as noted by McCabe(1984), this is analagous to interpreting all carbonates as shallow marine sediments. Modern peat accumulations occur in a variety of restricted environments, including delta-bayfill, back-barrier-lagoonal, estuarine and fluvial overbank settings. It is difficult to make environmental interpretations of coals based only on the depositional facies of the enclosing strata as the exact age relationships are difficult to resolve in modern and ancient strata (Cohen 1984). Moreover, few modern analogs for thick coal deposits have been described as most modern peats have a relatively high clastic content which would compact to form carbonaceous shales, and not clean coals (McCabe 1984).

Only a few modern peat-forming environments appear capable of forming the thick, non-shaly coals of facies 9A which are typically developed above a regressive marine sandstone. In tidally-influenced coastal settings in humid tropical climates (e.g. Klang-Langat delta), densely vegetated raised swamps are commonly developed in a supratidal environment (McCabe 1984). These swamps consists of elevated islands of peat, rising up to 7 meters above the surrounding tidal channels. These raised swamp peat bogs may exceed 13 m in thickness (McCabe 1984) and typically have very low clastic content as the steep margins tend to divert sediment-charged floodwaters away from the peat. Similar clean (mud-free) peats up to 5.9 m in thickness have been described in the freshwater swamp-marsh complex in the Okefenokee Swamp of the Georgia Coast (Cohen 1984). The clean coals capping the regressive Hoadley-Medicine River and Torrens Member sandstones could have been deposited in either setting although the Okefenokee model is favoured as there is little evidence of a strong tidal influence in the strata associated with these coals.

These coals above the Glauconite and Moosebar sandstones are very dissimilar to clastic rich estuarine-lagoonal peats deposited behind barrier islands, as described by Cohen (1984). This is significant as it implies that the Hoadley-Strachan Complex prograded seaward as a shoreline-attached strandplain (Reinson 1984) without an associated lagoon, and is thus not a barrier complex as Chiang (1984) suggested.

The clean Medicine River Coal is more difficult to interpret as it is thick, widely distributed and interbedded with non-marine strata. Ryer (1984) has noted that the thickest coals in the Western Interior are developed near the points of maximum transgression and regression of the Interior Seaway. The Medicine River Coal fits this model because it is stratigraphically equivalent to, and developed landward of, a thin transgressive marine shale which overlies the Torrens-Modeste Creek sandstone in the northern part of the study area (see chapter 6). This transgression presumably resulted in a rise in relative base level which would create "slowly shifting shorelines and periods of stagnation" (McCabe 1984) which were ideal peat-forming conditions. The rise in base level could elevate the water table and decrease the sediment-carrying capacity of the river systems, such that that little clastic sediment was introduced into the poorly drained peat swamps in the lower coastal plain.

The carbonaceous shales of facies 9B could have been deposited in a variety of marginal and non-marine environments. The rare occurrence of carbonaceous shales capping the Hoadley Member (e.g. 7-12-38-9W5) suggests that some form of restricted embayment, analgous to Cohen´s (1984) lagoonal salt marsh, may have been present behind the shoreline at certain times. The carbonaceous shales of subfacies 9B in the Gladstone Formation are associated with non-bioturbated, extensively rooted sediment which presumably records non-marine overbank deposition in a low-lying coastal plain setting. In the equivalent Ellerslie Formation in the subsurface, the carbonaceous shales are interbedded with brackish to restricted marine sediments (subfacies 7C) and apparently record periodic emergence estuarine or lagoon. Petrographic analysis would be required for more detailed interpretation of the coals.

(6) DEPOSITIONAL SEQUENCES AND REGIONAL CORRELATIONS

Dramatic lateral and vertical facies changes in the Mesozoic clastic wedge have obscured stratigraphic correlations within the Western Canadian Sedimentary Basin. These correlation problems, in turn, have obscured the depositional history of the basin and prevented accurate reconstruction of the basin paleogeography. This chapter will open with a discussion of the regional correlations within the Blairmore-Luscar interval in the Foothills and the Mannville in the western Plains and will close with a discussion of outcrop-subsurface correlations and the depositional history of the basin.

(A) FOOTHILLS CORRELATIONS

To resolve the correlation problems in the Foothills, twelve outcrop exposures were measured between Sheep River and Grande Cache, Alberta. In this area, the Early Cretaceous succession can be divided into three distinct stratigraphic intervals:

1) a basal conglomerate overlain by a muddy non-marine interval (Cadomin and Gladstone Formations).

2) a middle muddy interval which is dominated by brackish to lacustrine bioclastic limestones in the southern Foothills (Calcareous Member of Glaister,1959) and open marine shales in the central Foothills (Moosebar Formation).

3) an upper non-marine unit which is comprised of coarse feldspathic sandstones (Beaver Mines Formation) in the southern Foothills and coal-bearing sandstones and mudstones (Gates Formation) in the central Foothills.

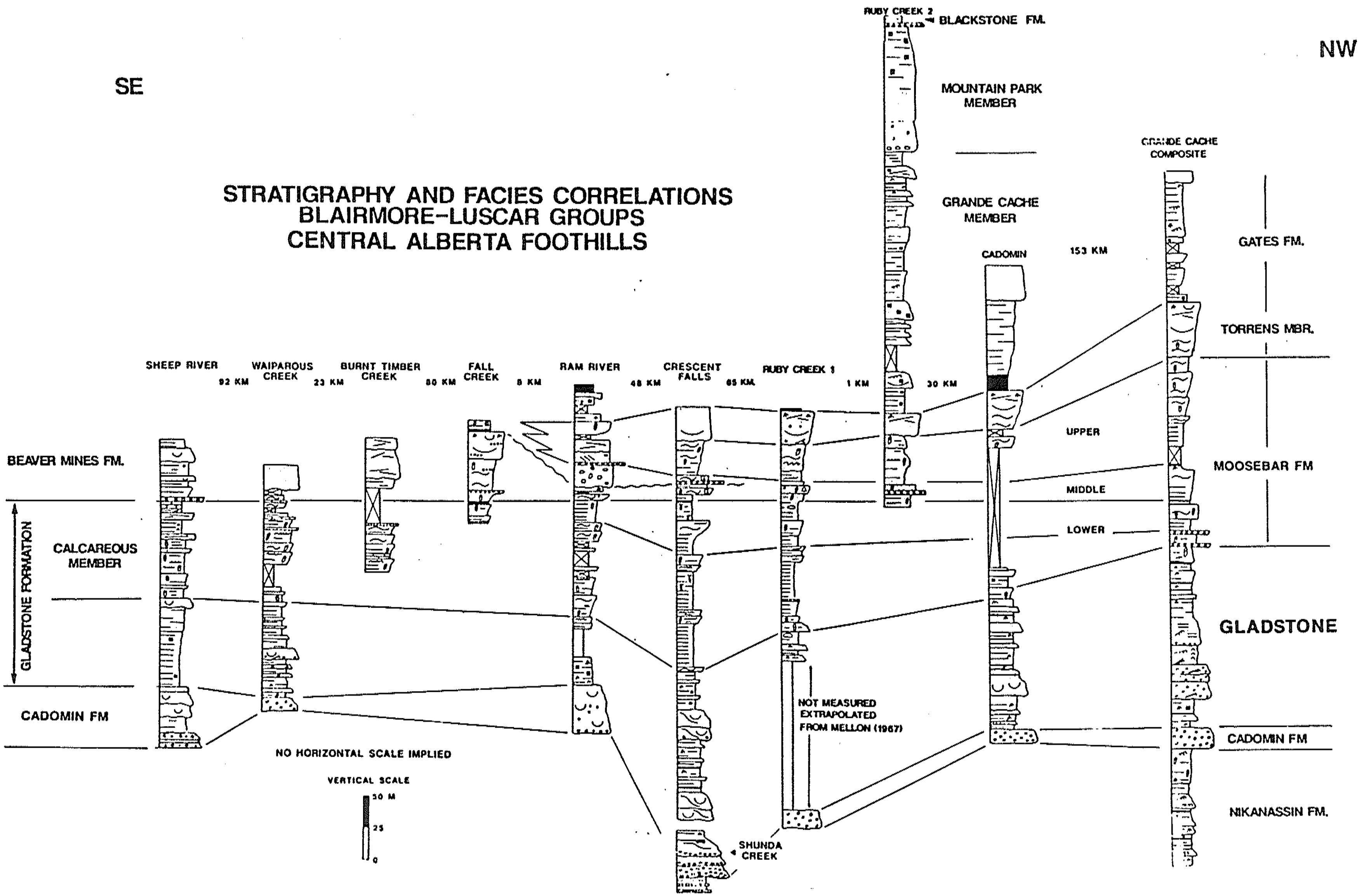
To describe the lateral facies changes recognized along the length of the Foothills, the outcrops in the southern and central Foothills will be described separately and the correlations between these areas will be discussed later.

(i) SOUTHERN FOOTHILLS

Five Blairmore outcrops were examined in the southern Foothills (Gladstone Creek, Sheep River, Elbow Falls, Waiparous Creek and Burnt Timber Creek). Two of these sections (Waiparous and Burnt Timber Creek) were measured in detail and these data are plotted on the cross sections (Fig. 17, Appendix 3B).

The base of the Blairmore is marked by a conglomerate or pebbly sandstone (Cadomin Formation) which overlies an unconformity at the top of the underlying (coal-bearing) Kootenay Formation. In the Waiparous Creek section, the basal pebbly sandstone is 8m thick and grades upwards into approximately 50m of rooted carbonaceous mudstones (facies 7A) which contains a 5m-thick, trough cross-bedded channel sandstone. In other sections, the Cadomin appears to fine-upwards into the overlying Gladstone and no discrete channel sandstones are developed within the Gladstone interval.

The contact of the non-marine Gladstone and the overlying bioturbated muddy interval (Calcareous Member) was not exposed in either the Waiparous or Burnt Timber Creek sections. This bioturbated interval is at least 90 m thick in the Waiparous Creek section and is comprised of numerous, meter-scale coarsening-upward sequences. Each sequence is comprised of bioturbated calcareous shales (facies 1A, 2B) at the base and wave-rippled and hummocky cross-stratified sandstones with synaeresis cracks (facies 2B, C) at the top. No signs of emergence (e.g. roots) were recognized at the top of these units although several cycles were capped with shaly bioclastic lime wackestones. In the terminology employed by Glaister (1959), only the uppermost (10-15m) part of the interval containing the limestone beds would be mapped as Calcareous Member and the underlying bioturbated, wave-rippled interval would be included in the middle part of the Gladstone Formation. However, from a sedimentological



(17) Stratigraphic cross section showing lithostratigraphic correlations within Blairmore and Luscar Groups, central Alberta Foothills.

perspective, the contact of the bioturbated wave-rippled shales with the underlying rooted, carbonaceous mudstones is more significant as it records the initial advance of the brackish Clearwater-Moosebar Sea in this area (Fig. 6B). For this reason, it is recommended that the term Calcareous Member be used to describe the entire interval of bioturbated, wave-rippled sandstones, shales and limestones developed between the basal (non-marine) part of the Gladstone and the overlying Beaver Mines Formation.

In the Gladstone Creek and Sheep River sections, the Calcareous Member is capped by a dark greenish-black shale. The sharp basal contact of this shale is probably an unconformity surface as it is marked by a cm-thick pebbly veneer in the Sheep River section. Marine dinoflagellates were recovered from this shale in the Gladstone Creek (SH-14, Table 5) and Sheep River exposures (G.Nadon, pers. comm. 1986). This greenish-black mudstone is overlain by coarse, greenish-grey feldspathic sandstones of the Beaver Mines Formation in all outcrops in the southern Foothills. The Beaver Mines sandstone is typically structureless to crudely stratified (facies 8A) and occasionally cross-bedded (facies 8B, C). Thin (1-10 cm) discontinuous lenses of chert pebbles are scattered throughout the sandstone. No complete sections of the Beaver Mines sandstones have been reported although Mellon (1967) estimated that the thickness ranged from 900-1200′ (300-400 m).

(ii) CENTRAL FOOTHILLS

Seven outcrops of Blairmore-Luscar strata were measured in the Central Foothills (Fig. 17). In this area, a modified version of Langenberg and McMechan′s (1985) terminology was used to describe the strata (Fig. 3B). In some areas (e.g. Nordegg, Grande Cache), no complete sections of the Blairmore-Luscar interval were exposed and composite stratigraphic sections were constructed by "piecing together" closely spaced outcrops which exposed different parts of the succession. Each of the stratigraphic units will be described separately in the following section.

CADOMIN FORMATION

The Cadomin Formation was exposed in the Ram River, Shunda Creek, Ruby Creek, Cadomin and Grande Cache sections. In all exposures, the Cadomin consists of a clast-supported, chert-pebble conglomerate (facies 8E) with minor sandstone interbeds (facies 8A, B). The base of the Cadomin is invariably abrupt and the contact with the overlying Gladstone was either gradational (e.g. Shunda Creek, Grande Cache) or abrupt (e.g. Cadomin). The thickness of the Cadomin ranged from 11m (Grande Cache) to 16m (Shunda Creek). In outcrop, the Cadomin conglomerate is massive to crudely stratified and contains no cross-bedding or apparent imbrication. In the Shunda Creek section, five fining-upward sequences were recognized. Each consisted of clast-supported conglomerates grading upwards into pebbly, medium to coarse-grained parallel-laminated sandstones (facies 8A).

GLADSTONE FORMATION

Thick sections of the Gladstone Formation were exposed in the Crescent Falls and Grande Cache outcrops and shorter sections were exposed in the Ram River, Shunda and Ruby Creek sections. In all exposures in the central Foothills, the Gladstone consists of rooted, carbonaceous mudstones and sandstones (facies 7A) interbedded with structureless to crudely bedded, cross-stratified channel sandstones (facies 8). The thickness of the Gladstone Formation ranges from 65m (Ram River) to 100m (Grande Cache). In the Cadomin outcrop, the Gladstone interval is badly faulted and the true stratigraphic thickness could not be determined. The significance of these thickness variations is difficult to evaluate since the contact with the Cadomin is gradational in some exposures (e.g., Grande Cache) and thick conglomerates included in the Gladstone may actually comprise part of the Cadomin interval.

In the Crescent Falls section, the Gladstone Formation contains two thick (14-16m) sharp-based, fining-upward channel sandstones which are separated by 34 m of rooted (overbank) sediments. Both channels are floored by a thin pebbly lag and exhibit excellant lateral accretion surfaces (Fig. 19A). Taylor and Walker (1984) reconstructed paleohydraulic parameters of these channels and suggested they were deposited by highly sinuous streams with depths of 8 m and widths of 30-58 m. In the Grande Cache section, a thick fining-upward succession comprises the upper part of the Gladstone Formation. This succession is floored by a 17m-thick conglomerate and grades up into sandstones, thin coals and carbonaceous rooted mudstones. Overall, the Gladstone interval is much coarser-grained in the Grande Cache section than in all other sections examined.

MOOSEBAR FORMATION

Complete sections of the Moosebar Formation were exposed in the Ram River, Crescent Falls, Ruby Creek 1, and Grande Cache outcrops and short sections were exposed in the Fall Creek, Ruby Creek 2, Cadomin and Tay River outcrops (Fig. 17, Appendix 3B). In general, the Moosebar consists of brackish to marine shales and sandstones which ranged in thickness from 80m (Grande Cache) to 110m (Crescent Falls). The contact with the underlying Gladstone is typically abrupt and the contact with the overlying Torrens marine sandstone (Gates Formation) is gradational. In the central Foothills, three depositional sequences are recognized in the Moosebar (Fig. 19B). The thickness, depositional facies and

Figure 18 Outcrop photos of representative sedimentary structures, Blairmore-Luscar Group.

(A) Outcrop photo of synaerisis cracks in interbedded sandstone and mudstone (Facies 7C). In plan view, these structures exhibit characteristic spindle shapes. Photo taken 2 meters below top of lower Moosebar interval, Bighorn River outcrop. Lens cap for scale.

(B) Outcrop photo of symmetrical wave ripples at top of ultraquartzose sandstone at top of lower Moosebar Formation, Crescent Falls section. Orientation of long axis of ripples at this locality approximately 70/250. Hammer for scale.

(C) Outcrop photo of parallel lamination, top Torrens Member (Gates Formation), McIntyre Mines outcrop, Grande Cache area. Hammer for scale.

(D) Outcrop photo of intraclastic breccia near the base of the feldspathic Beaver Mines sandstone, Ram River outcrop. Lens cap for scale.

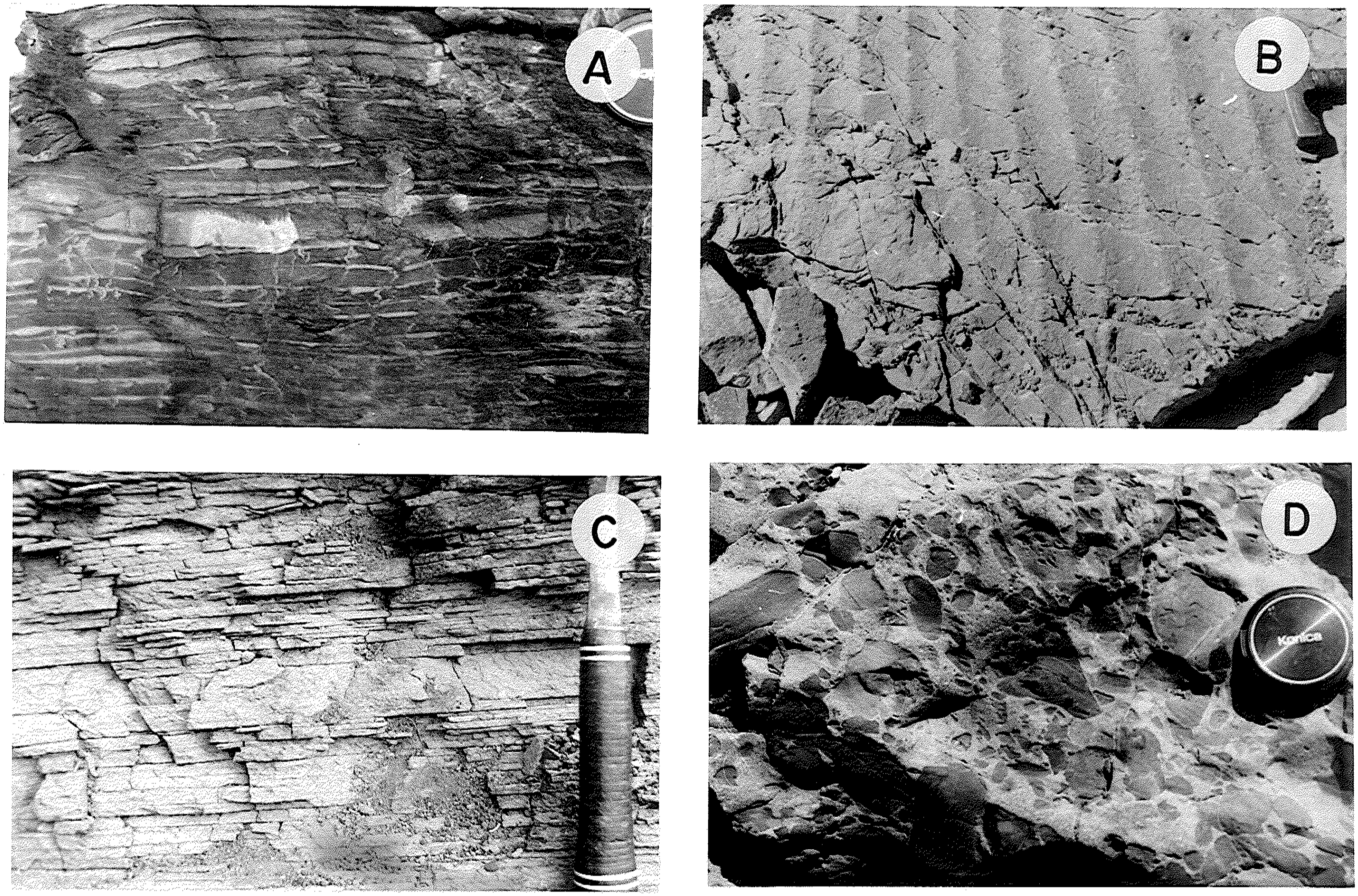

A
B
C
D
Konica

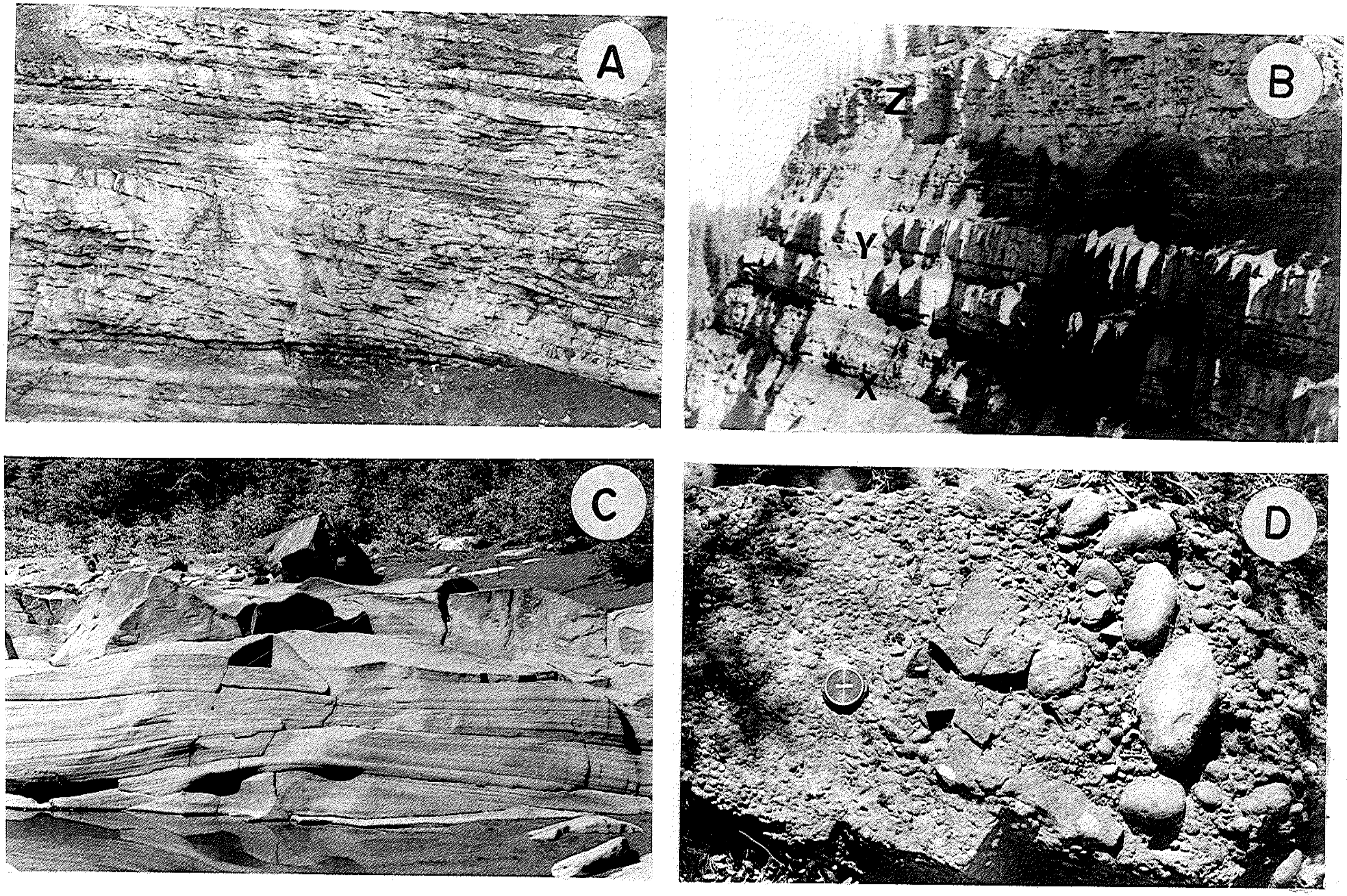
Figure 19 Outcrop photos of Blairmore-Luscar strata

(A) Outcrop photo showing large-scale lateral accretion surfaces in trough cross-stratified non-marine channel sandstone in Gladstone Formation. Base of channel is approximately 50m above base of measured section, Crescent Falls outcrop. Field of view approximately 50m.

(B) Outcrop photo showing 3 marine sandstone cycles in the Moosebar Formation, Crescent Falls outcrop. The lower and uppermost sandstones exhibit coarsening-upward trends and Y marks the thin conglomerate at the sharp base of the middle sandstone. X marks the thin coal horizon at the top of the lower Moosebar; Z marks the Torrens Member (Gates Formation). Approximately 60 m of section exposed in field of view.

(C) Outcrop photo of hummocky cross-stratified sandstone (Facies 4A). Note abundant curviplanar low angle truncation surfaces and absence of angle of repose stratification. Lower "twin sandstone", middle Moosebar, Bighorn River outcrop located 2.5km upstream of Crescent Falls. Field of view approximately 5 meters.

(D) Outcrop photo of clast-supported pebble/cobble conglomerate developed at base of Glauconitic upper "twin sandstone", middle Moosebar interval, Bighorn River section. Camera lens for scale.


A
B
Z
Y
X
C
D

microfossil content of each succession changes along the length of the Foothills. These sequences are informally termed the lower, middle and upper members and will be described separately in the following section.

The lower member of the Moosebar consists of a thick section of black, bioclastic shales (facies 1B) which contain variable proportions of bioturbated, wave-rippled sandstones (facies 2B, C). The basal contact of the lower Moosebar is generally abrupt and the top is marked by a carbonaceous shale or coal. The thickness of this unit ranges from 20m (Grande Cache) to 76m (Crescent Falls). This interval contains several thin (2-5m) coarsening-upward sequences which are capped by hummocky cross-stratified, wave-rippled sandstones (Facies 2B, C). In the Crescent Falls section, the lower Moosebar is capped by a 6m-thick, highly quartzose, very fine-grained marine sandstone (facies 4B). This sandstone is overlain by 5 meters of brackish-water mudstones (facies 7C) which contains abundant synaerisis cracks (Fig.18D) and is capped by a 20 cm-thick coal. The trace fossils Planolites, Teichichnus, and Paleophycus were observed at the base of this quartzose sandstone. Four samples of the lower Moosebar shales were processed for microfossils (SH-107, 110, 113, and 116, Table 5) and all contained a freshwater-to brackish ostracode assemblage.

The base of the middle Moosebar consists of open marine shales (facies 1A) and wave-rippled sandstones and mudstones (facies 2B, C) which abruptly overly the thin coal at the top of the lower Moosebar. In the south-central Foothills (e.g.,Fall Creek), the middle Moosebar shales are overlain by a coal-capped sandstone whereas further north, the middle Moosebar shale is overlain by pebbly, glauconitic marine sandstones. In the Crescent Falls section, two thick marine sandstones are recognized in the middle Moosebar (Fig. 19B) and these were informally termed the "twin" sandstones by Taylor and Walker (1984).

Samples of the middle Moosebar shales contain a meagre foram-ostracode assemblage which was interpreted as marine (Taylor and Walker 1984). An open marine environment is also supported by the abundant glauconite and presence of a diverse trace fossil suite including Planolites, Rhizocorallium, Asterosoma, Teichichnus and Paleophycus in the middle Moosebar sandstones. In the Crescent Falls area, the lower twin sandstone has a gradational base and is highly bioturbated whereas the upper twin sandstone has a sharp base (containing chert cobbles to 10 cm in diameter (Fig. 19D) and contains excellant hummocky cross-stratification (Fig. 19C).

In the Fall Creek section, a thick (30m) regressive marine sandstone is developed in the middle Moosebar and this section is capped by a rooted carbonaceous shale (Fig. 17). Overall, this sandstone is massive to structureless (facies 4E) although parallel laminated and hummocky-cross stratified sandstones (facies 4A, B) are developed immediately below the rooted zone. This sandstone contains a few thin (<10 cm) sharp-based conglomerate beds near the top of the section. In other outcrops in this area (e.g. Tay River) the middle Moosebar sandstone is capped by a thick (5.0m+) clast-supported conglomerate with a sandy matrix (facies 5B). In the Ram River section, the Middle Moosebar has been scoured out, and replaced by, a Beaver Mines channel sandstone (Fig. 17). A thick clay pebble breccia (Fig. 18D) is developed near the base of this channel sandstone.

The upper Moosebar shale is not recognized south of the Crescent Falls section. Where present, this shale abruptly overlies marine sandstones of the middle Moosebar and is overlain by the Torrens sandstone (Fig. 19B). This interval consists of fissile black shale (facies 1A) which grades upwards into wave-rippled and hummocky cross-stratified sandstones (facies 2B,C) at the base of the overlying Torrens sandstone (Fig. 17). Only one sample of this shale was processed for microfossils (SH-111) and this contained a diverse (open marine) foraminiferal assemblage (Table 5).

GATES FORMATION

Only one complete section of the Gates Formation was measured in this thesis (Ruby Creek) although the basal sandstone (Torrens Member) was measured in all of the central Foothills outcrops (Fig. 17). In the Ruby Creek, Cadomin, and Grande Cache sections, the Torrens Member is a massive to crudely-laminated feldspathic sandstone (facies 4A, B) which is capped by a rooted carbonaceous shale or coal (Fig. 17). In the Ruby Creek section, the Torrens sandstone is exposed on two separate thrust sheets, each of which displays a different facies sequences. In Ruby Creek 1, the Torrens is relatively thin (9.5m) and the unit appears to scour down into the underlying upper Moosebar shale. In the second exposure, the Torrens is much thicker (30m), has a gradational base and contains a clay and chert-pebble lag (facies 8E,F) overlain by highly carbonaceous sandstones (facies 8C) and parallel laminated sandstones (facies 4B). In the Crescent Falls section, the top of the Torrens Member is not exposed.

The upper part of the Gates Formation (Grande Cache and Mountain Park Members) was examined in the Ruby Creek, Cadomin and Grande Cache areas although only the Ruby Creek section was measured in detail (Fig. 17). In this section, the Grande Cache Member is 144m in thickness and consisted of structureless to crudely bedded, greenish-grey carbonaceous rooted mudstone (facies 7A) interbedded with crudely bedded sandstones. The overlying Mountain Park Member is a 70 m-thick, crudely stratified channel-form sandstone which contains a 2 m-thick clay pebble lag at the base. This sandstone fines-upwards and the upper 20m consists of carbonaceous muddy sandstones. The Mountain Park

Member is capped by a 60cm chert pebble conglomerate and overlain by marine shales of the Alberta Group (Fig. 17).

(B) SUBSURFACE FACIES SEQUENCES AND STRATIGRAPHIC CORRELATIONS

Subsurface correlations in the Jurassic-Early Cretaceous clastic wedge of western Alberta are poorly understood, primarily because most previous studies have not integrated facies and micropaleontological data with geophysical log data. To establish the regional correlations across the study area, a series of east-west oriented stratigraphic cross-sections were constructed for every township across the area TWP40-TWP55, between the fifth meridian and the eastern limit of the disturbed belt. Four north-south cross sections were also run to establish the correlations between these east-west cross sections. The sections employed a top Mannville datum and preliminary correlations were established by plotting ERCB (Energy Resources Conservation Board) formation tops for the Glauconite, Ostracode, Ellerslie, and Jurassic intervals.

In general, the ERCB formation tops were of limited use as they employed different criteria and nomenclature to define the formation tops in different areas. When the core data was integrated with the log sections, a series of marker beds with distinctive core or log signatures were recognized and these formed the framework for a revised stratigraphic nomenclature scheme. Four stratigraphic units were differentiated in the study area on the basis of core lithofacies and their geophysical log signature and these include:

Fernie Formation.

Ellerslie Formation.

Glauconite Formation.

Upper Mannville (undifferentiated).

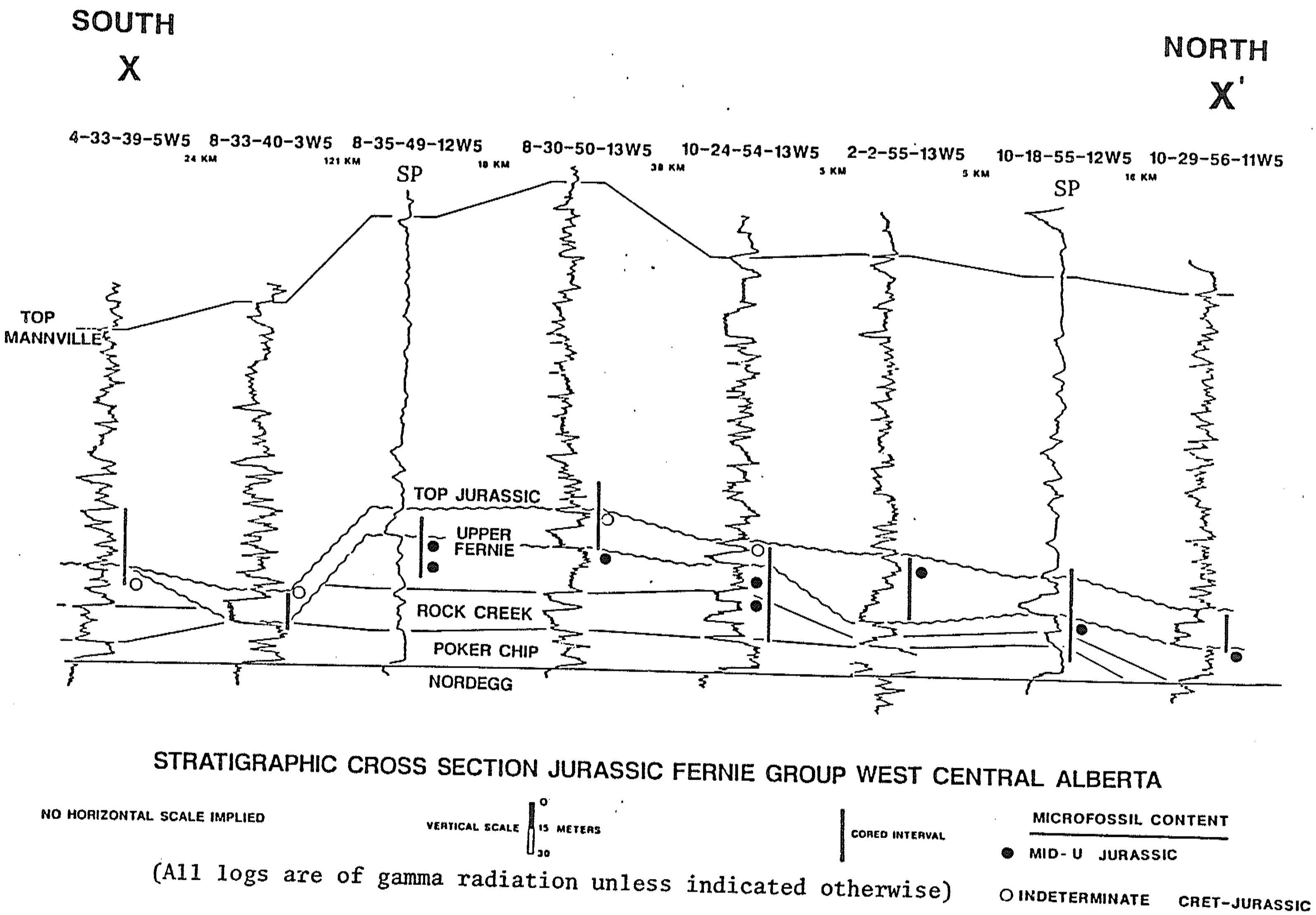
Two of these intervals (Glauconite and Fernie Formations) were further subdivided into several members and detailed description of each of these units is presented in the following section.

(i) FERNIE FORMATION

In the subsurface of western Alberta, the Fernie Formation is represented by a complex sequence of unconformity-bounded shale, sandstone and carbonate units which exhibit dramatic facies and thickness changes across the study area. Previous subsurface studies (e.g.,Marion 1984) recognized four units in the Fernie (Nordegg, Poker Chip, Rock Creek and Upper Fernie) and this terminology is employed in this study although the upper contact of the Upper Fernie has been revised slightly. A stratigraphic cross section showing the GR signature of the Nordegg, Poker Chip, Rock Creek and Upper Fernie units and the age of shales, based on microfossils, is shown in Fig. 20. An isopach map showing the composite thickness of the Poker Chip, Rock Creek and Upper Fernie Members is shown in Fig. 21. A schematic cross-section showing the stratigraphic relationship between the unconformity-bounded members of the Fernie Formation is shown in Fig.22.

Nordegg Member

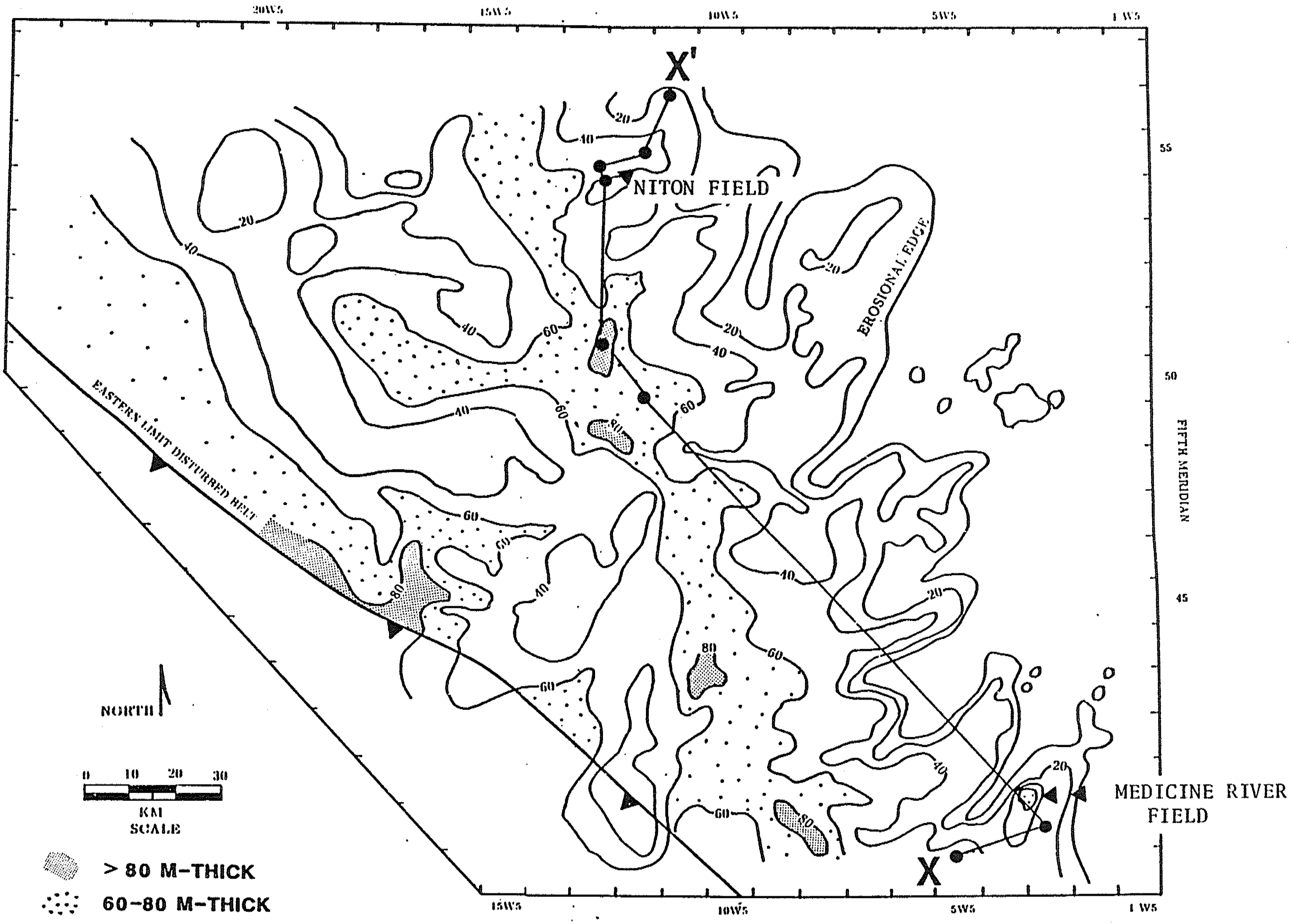
The Early Jurassic (Nordegg) Member is a shaly chert-carbonate interval which is difficult to differentiate from the underlying Paleozoic carbonates in the subsurface. Springer et al.(1964) noted that the Nordegg consists of chert and deep-water shales in the Foothills and western Plains and shallow water carbonates and clastics in the west-central Plains, near its subcrop edge. As the Nordegg interval was only cored in a few wells, the sedimentology of this interval could not be studied in detail. In most of the Nordegg cores examined in this thesis (e.g.,6-18-54-7W5 and 6-35-43-7W5), the interval consists of silicified lime mudstones and wackestones containing sponge spicules and



STRATIGRAPHIC CROSS SECTION JURASSIC FERNIE GROUP WEST CENTRAL ALBERTA

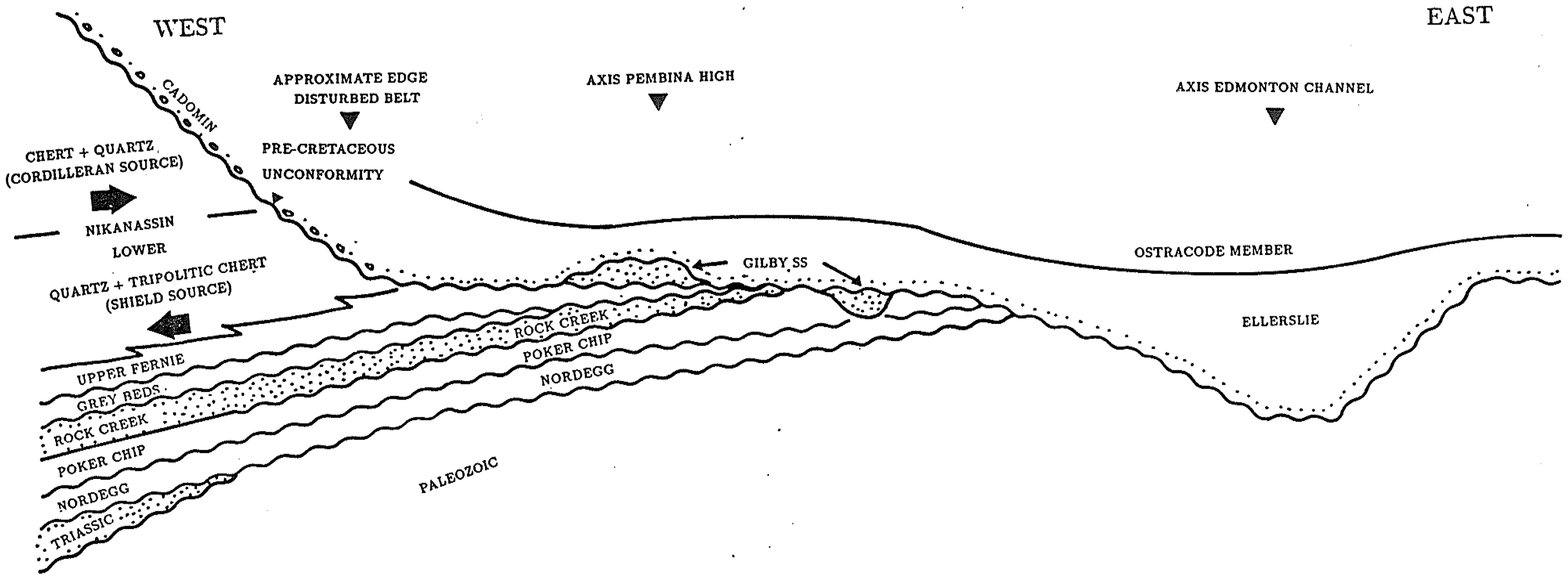
(All logs are of gamma radiation unless indicated otherwise)

(20) Subsurface stratigraphic cross section, Jurassic Fernie Formation, west central Alberta.



(21) Isopach map, Jurassic strata from top Nordegg to pre-Cretaceous unconformity (composite Poker Chip, Rock Creek, and Upper Fernie Members).

X-X' shows location of cross section shown in Fig.20



(22) Schematic cross-section showing stratigraphic relationship between mappable, unconformity-bounded members of the Fernie Formation.

crinoids (facies J5) which were overlain by bioturbated quartzose sandstones (facies J4). However, in one core (i.e.,13-32-38-4W5), the Nordegg consists of a medium-grained cherty sandstone. The relationship between the different facies described above could not be established with the limited number of cores examined in this thesis. The contact of the Nordegg with the overlying Poker Chip shales was cored in two wells (e.g., 6-32-49-3W5 and 4-4-51-4W5) and in both cases it is marked by a regolith-breccia (facies J-6) which probably represents an unconformity surface.

Poker Chip Member

In the western Plains, the term Poker Chip is used to describe a light grey-green clean (non-sandy) shale which is developed between the Early Jurassic Nordegg Member and the Middle Jurassic Rock Creek Member. This shale is correlated with the black fissile shales of the Early Jurassic Poker Chip Member of the Foothills although this correlation has not been confirmed with paleontologic data. The Poker Chip shale reaches a maximum thickness of 25m in the central Plains and thickness variations are primarily due to differential erosion below the pre-Cretaceous unconformity. The contact with the overlying Rock Creek was only cored in two of the wells examined (i.e., 6-11-50-9W5 and 11-25-54-12W5) and in both cases, the abrupt contact is marked by a thin pebbly horizon.

Rock Creek Member

The Rock Creek Member consists of bioturbated, highly quartzose marine sandstones (facies J4) which is locally interbedded with sandy mudstones (facies J2C) and rarely with bioclastic limestones (e.g., 7-3-49-9W5). The correlation of this unit with the Middle Jurassic (Bajocian) sandstone in the

Foothills has been confirmed by the presence of an ammonite of that age at the top of the Rock Creek sandstone in a drill core in the western Plains (Marion 1984). A slightly younger (Middle Jurassic) age (Bathonian-Callovian) is indicated by the pollen assemblages recovered from shales interbedded with these sandstones (Fig. 20) but the reason for this apparent age discrepancy could not be established. The Rock Creek unconformably overlies the Poker Chip Member in most sections (e.g. 11-25-54-12W5) although near its subcrop edge, it may onlap the Nordegg carbonates (e.g. 6-35-43-7W5). The contact with the overlying Upper Fernie is abrupt and marked by a silicified, pyritized alteration zone (facies J6) which is capped by a glauconitic, pebbly sandstone (e.g. 7-11-49-10W5). An isopach map of net clean sandstone in the Rock Creek Member could not be constructed, due to the paucity of core control although several general trends were recognized. The thickest Rock Creek sandstones were developed in the central part of the study area where three sandstones, separated by marine shales, are developed (e.g. 10-24-54-13W5, Fig. 20). The sandstone thinned to the west, presumably due to a facies change into more argillaceous facies and the unit was completely absent in the east, due to truncation along either the pre-Upper Fernie or pre-Cretaceous unconformities (Fig. 22).

Upper Fernie Member

The term Upper Fernie was introduced by Marion (1984) to describe the Jurassic strata above the Rock Creek sandstone and below the pre-Cretaceous unconformity. Marion (1984) reported that the Upper Fernie was generally less than 5m in thickness in the west-central Plains. However, the Jurassic-Cretaceous contact was very difficult to pick in core and on logs and microfossil data will be presented in this section which confirm that most of the strata included in the Early Cretaceous Ellerslie-Basal Quartz interval by Marion (1984) are actually Middle to Late Jurassic in age. This is significant because this interval includes the reservoir sandstones in several important fields in the study area (e.g. Niton, Medicine River, Fig. 21). A maximum of 45 m of Upper Fernie strata was present in the 8-30-50-13W5 well (Fig. 20).

The basal Upper Fernie typically consists of dark ribbon facies shales (facies J2B). Eleven samples of these shales were processed for microfossils (Table 2) and most yielded a Late Jurassic age although one sample in the Niton area (SH-87, Table 2) produced a Middle Jurassic assemblage. The upper part of the Upper Fernie consists of interbedded dark and light ribbon mudstones (facies J2A, B) interbedded with thick (2-10 m) highly quartzose, structureless to crudely stratified sandstones (Facies J3 and J4). These sandstones comprise part of either coarsening-upward (e.g. 4-33-39-5W5) or fining-upward (e.g. 8-33-40-3W5) successions and there is no evidence of emergence (i.e. paleosols, roots) at the top of these sequences. These quartzose sandstones are generally capped by light ribbon facies mudstones (facies J2A) and the two samples of these shales processed for microfossils (SH-2) did not yield any age-diagnostic fossils.

SUMMARY FERNIE FORMATION

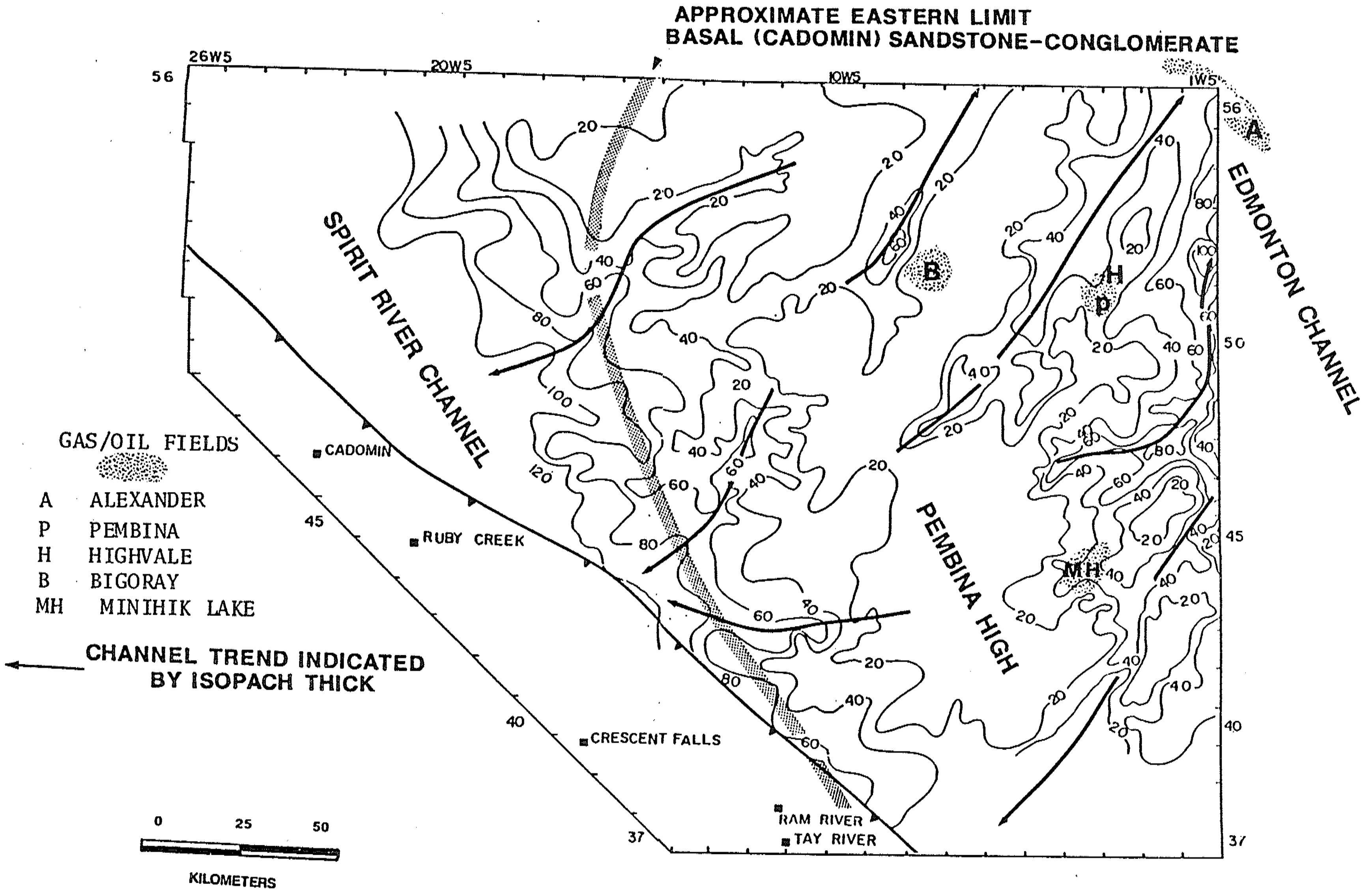
The Fernie Formation in the study area is represented by a series of condensed marine sequences which are bounded by paleosols and exposure surfaces. The Early Jurassic is represented by a basal shaly limestone and chert interval (Nordegg Member) which is overlain by open marine shales (Poker Chip Member). The presence of an unconformity between these units suggests that part of the Early Jurassic record is missing. The Middle Jurassic is represented by bioturbated open marine sandstones of the Rock Creek Member.

These sandstones exhibit a widespread, sheet-like geometry and probably represent shelf deposits. The Upper Fernie is Late Jurassic in age and consists of open to restricted marine shales which unconformably overlie the Rock Creek Member. These mudstones are interbedded with thick, highly quartzose sandstones which were previously considered to be Early Cretaceous in age. These sandstones probably represent Late Jurassic shelf deposits which are equivalent to the Swift Formation of the southern Plains (Hayes 1983) although their exact age has not been unequivocally established.

(ii) ELLERSLIE FORMATION

The Ellerslie Formation includes all strata between the pre-Cretaceous unconformity and a limy bioclastic shale (facies 1B) which can be recognized throughout the study area. This shale was termed the Ostracode Zone by Loranger (1951) and in this study is mapped as the basal unit (Ostracode Member) of the Glauconite Formation (Fig. 9). In some cores (e.g., 6-32-50-8W5), the Ellerslie is absent and the Ostracode marker rests directly on the pre-Cretaceous unconformity. The Ellerslie reaches a maximum thickness of 192m near the eastern limit of the disturbed belt (i.e., 14-30-46-18W5) although the thickness is less than 30 meters over most of the study area. The thickness variations across the study area can be seen on a gross isopach map which was constructed using data from approximately 1000 wells in the area (Fig. 23). The thickness differences on this map reflect irregular topography on the top of the pre-Cretaceous unconformity. In general, the interval is thin to completely absent in the central part of the study area (Pembina High, Fig. 23) and thickens westward into the Spirit River Channel and eastward into the Edmonton Channel.

The Ellerslie Formation was cored in only a few wells as it does not constitute an important reservoir in the study area. It typically consists of



(23) Isopach map, Early Cretaceous (Mannville) strata between base of the Ostracode Member and pre-Cretaceous unconformity.

brackish to non-marine mudstones (facies 7A, C) interbedded with thin bioturbated and trough cross-bedded sandstones (facies 7E, 8B, C).

The scarcity of cores and large thickness variations hamper subdivision of the Ellerslie Formation. Only two wells cored significant thicknesses of the Ellerslie Formation (e.g. 14-31-52-8W5, 10-15-50-7W5) and both contain a thick section of rooted non-marine strata (facies 7A) at the base of the interval. In most cores, the upper 10-30m of the Ellerslie interval consists of brackish to marine shales (facies 7B, 1A) interbedded with marine sandstones (facies 4). Marine dinoflagellates and freshwater to brackish ostracodes were recovered from a thin shale at the base of the marine sandstones in the Alexander field (Table 6, SH-3). This confirms that a strong marine influence was present in the basin, prior to the transgression represented by the Ostracode interval.

The thickness of this brackish-marine interval at the top of the Ellerslie increases to the north and east and in the extreme northeast corner of the study area (TWP56 R1W5, Fig. 23), a thick (5-10m) marine sandstone caps a coarsening-upward sequence developed at the top of the Ellerslie Formation. This marine sandstone forms a northwest-trending bar trend and comprises the reservoir in the prolific Alexander gas field (Fig. 23). Similar lithofacies are developed at the top of the Ellerslie along the crest of the Pembina High (e.g. Highvale-Bigoray fields) although the sandstones do not appear to exhibit a bar-like geometry in these areas.

In the Minihik Lake field (Fig. 23) the thin quartzose sandstone developed near the top of the Ellerslie Formation probably represents some type of channel deposit. This field is situated over a topographic low on the pre-Cretaceous unconformity (Fig. 23) and the cross-stratified sandstone which comprises the reservoir (e.g. 8-21-44-4W5) in this field appears to scour down into the underlying brackish mudstones (Fig. 16A). The origin of this channel could not be established with existing core control.

The thick clean sandstones comprising the Ellerslie Formation along the axis of the Edmonton Channel have been interpreted as fluvial to estuarine by Williams (1963) and Jackson (1984) and restricted marine by Bannerjee (1986). Only one well in the study area cored the Ellerslie sandstone in the Edmonton Channel (i.e. 1-32-56-26W4). In this core, the basal Ellerslie was comprised of bioturbated quartzose sandstone containing short, mud-lined Skolithos burrows (facies 7E). The presence of this bioturbated marine facies near the base of the Ellerslie interval supports Banerjee's (1986) suggestion that the Edmonton "Channel" is not actually a drowned-river valley, as Williams (1963) suggested, but rather is a broad, shallow restricted marine embayment. This interpretation will be discussed in more detail at the end of this chapter.

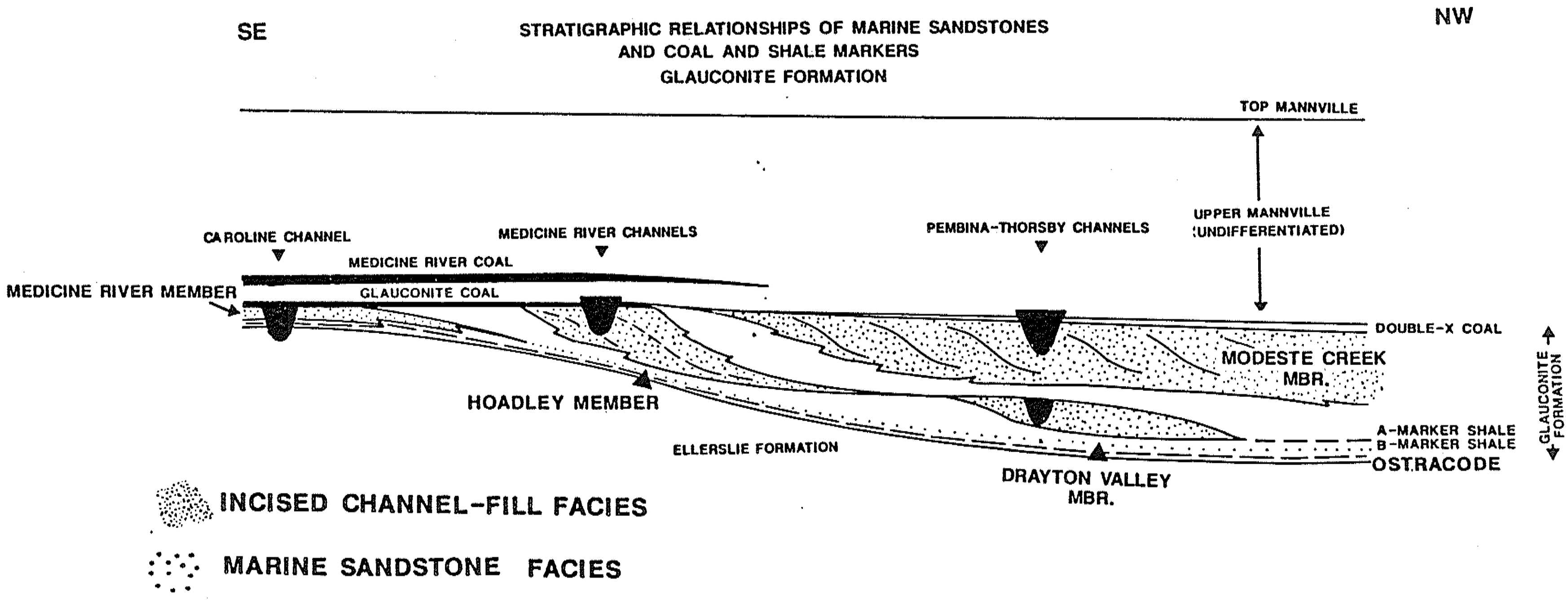
In the western Plains, near the eastern limit of the disturbed belt, thick clean sandstones which are developed at the base of the Ellerslie interval were correlated with the Cadomin conglomerate of the Foothills by the E.R.C.B. The distribution of this basal clean sandstone is plotted on the isopach map of the Ellerslie Formation (Fig. 23). The thick sand developed in the the Edson area is restricted to a northeast-trending low on the pre-Cretaceous erosion surface.

(iii) GLAUCONITE FORMATION

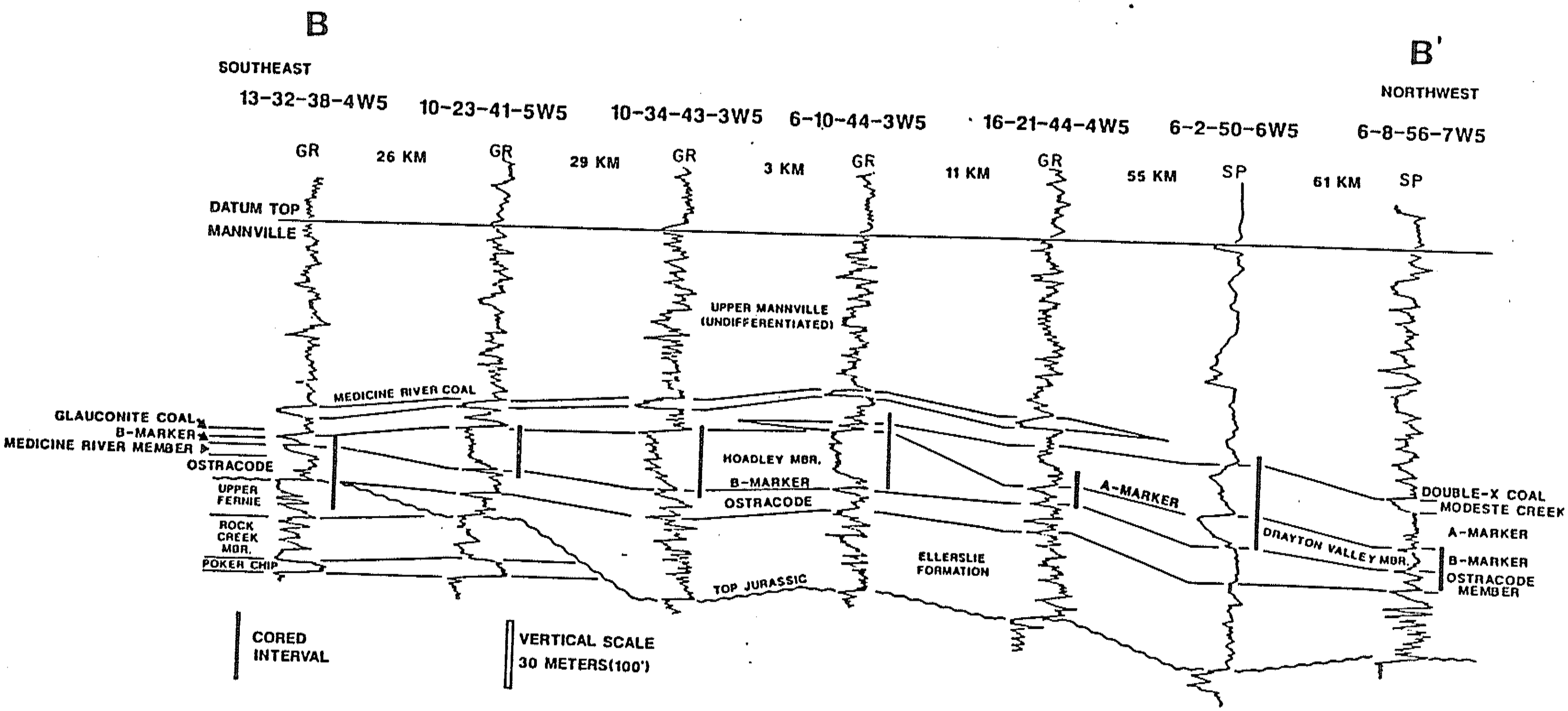
The Glauconite Formation consists of a northwesterly-thickening wedge of brackish to marine strata which separates the (non-marine to brackish) Ellerslie Formation from the overlying (non-marine) Upper Mannville section. The base of the Glauconite Formation is defined here as the base of the limy, bioclastic shale (redefined as the Ostracode Member,Glauconite Formation) and the top of the Glauconite Formation is marked at the top of the first coal overlying this marker shale. A gross interval isopach map was not constructed for the Glauconite Formation although a general northward increase in thickness was noted. An isopach map of meters clean sandstone (less than 33% shale on gamma-ray logs) was constructed for the Glauconite Formation to show the distribution of marine bar and incised channel trends in the study area (Fig. 11).

In west central Alberta, the Glauconite Formation consists of a series of sheet-like marine sandstones separated by thin marine shales, which are locally dissected by a series of incised fluvial channels. Four marine sandstones were recognized and each had different spatial and stratigraphic distribution. It is proposed in this study that each of these sandstones be awarded member status (Medicine River, Hoadley, Drayton Valley and Modeste Creek Members) and descriptions and type locations of each unit will be presented in the following section.

The relative age of the marine sandstones and incised fluvial channels was established by noting their stratigraphic position, relative to three regionally extensive shales (Ostracode, and A and B-markers) and two coal/carbonaceous shale horizons which are termed the Glauconite and Double-X Coals. A schematic cross-section showing the stratigraphic relationships between the marine sandstones, incised channels and the shale and coal markers described above is shown in Fig. 24. A cross section showing the log signature and stratigraphic relationship between these units is shown in Fig. 25. Proposed type sections (locations and description) for each of the marine sandstones in the Glauconite Formation are presented in the next section.



(24) Schematic cross-section showing stratigraphic relationship between marine sandstones, coal and shale markers, and incised channels in the Early Cretaceous Glauconite Formation, west central Alberta.



(25) Stratigraphic geophysical log section traversing the Medicine River, Hoadley, and Drayton Valley areas.

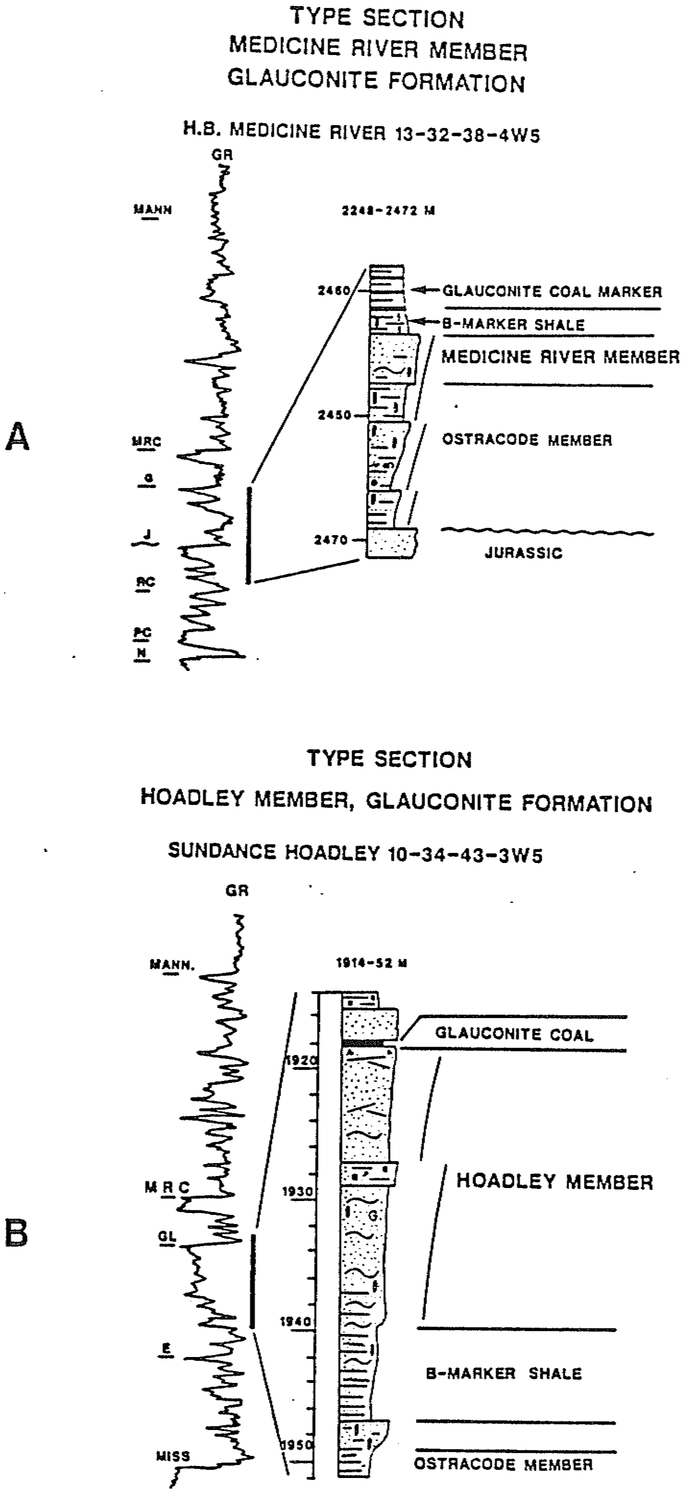
(a) MARINE SANDSTONES IN THE GLAUCONITE FORMATION

MEDICINE RIVER MEMBER

The term Medicine River Member is proposed to describe a thin, very fine-grained, quartzose marine sandstone which is developed just south of the Strachan-Hoadley trend (Fig. 11). The type section for this unit is the Hudsons Bay Medicine River 13-32-38-4W5 core (Fig. 26A). In this core, the base of the Glauconite (Ostracode Member) is marked by black bioclastic shales (facies 1B) overlain by bioturbated, wave-rippled sandstones and mudstones (facies 2B). The overlying Medicine River Member is a 4-m thick, fine-grained quartz arenite which is weakly bioturbated at the base and exhibits parallel and low-angle convergent lamination (facies 4B) near the top. This sandstone is capped by two meters of bioturbated sandy mudstone (B-marker shale) which is abruptly overlain by a rooted carbonaceous shale (Glauconite Coal). This sandstone has a thin sheet-like geometry which has been dissected by the northeast-trending Caroline Channel and the north to northwest-trending Medicine River channels (Fig. 11).

HOADLEY MEMBER

The term Hoadley Member is introduced to describe a marine sandstone developed in the middle part of the Glauconite interval in the southern part of the study area (Fig. 11). The Hoadley Member comprises the reservoir in the northeast-trending Hoadley gas field (Fig.11) and the proposed type section for this unit is the Sundance Hoadley 10-34-43-3W5 well (Fig. 26B). In the type area, the Hoadley Member consists of a 10-20 meter-thick, fine to medium-grained, slightly feldspathic litharenite. This sandstone caps a coarsening and thickening-upward sandstone/mudstone sequence above the B-marker shale and is overlain by the Glauconite Coal marker (Fig. 26B). The base of the sandstone is moderately bioturbated, slightly glauconitic and argillaceous

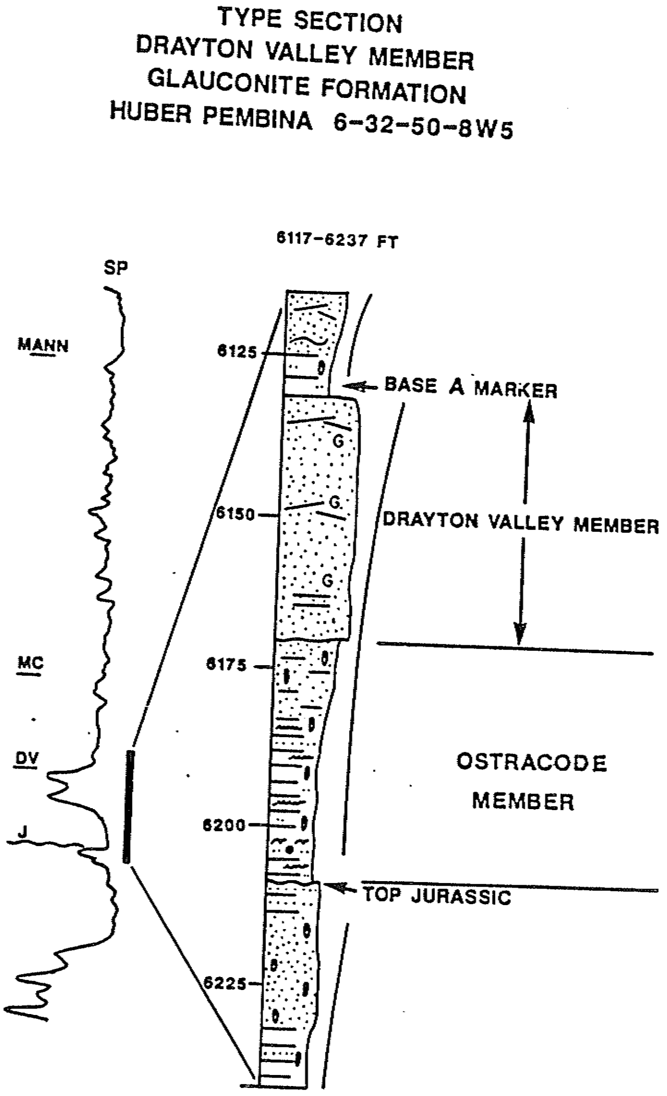


(26)(A) Log signature and core description for proposed type section, Medicine River Member, Glauconite Formation.
(B) Log signature and core description for proposed type section, Hoadley Member, Glauconite Formation.
(For legend see p. 271)

(Facies 3) whereas the upper part is dominated by parallel and low-angle convergent (beach) lamination (Facies 4B) and is capped by a thin rooted horizon. Along the southwest limit of this trend (i.e. Strachan area, Fig. 11), the upper 5-10 meters of the Hoadley Member consists of clast-supported chert pebble conglomerate (e.g. 10-22-37-9W5) which has a sandy matrix at the base (facies 5B) and grades upward into a matrix-free conglomerate (facies 5A). In a few cores in the type area, (e.g. 9-3-45-2W5), a second rooted horizon is developed approximately 10 meters below the upper rooted zones. The Hoadley-Strachan trend is intensely dissected by a series of northwest-trending, largely mud-filled channels (Fig. 11).

DRAYTON VALLEY MEMBER

The term Drayton Valley Member is proposed to describe a thick, glauconitic sandstone which forms a sheet-like sand body trending sub-parallel to, and located 30-50 km seaward of, the Hoadley trend (Fig. 11). In the type section (i.e. Huber Pembina 6-32-50-8W5), the sandstone contains 2-10% glauconite and consists of fine to medium-grained, slightly feldpathic chert litharenite which contains low-angle convergent laminations throughout (facies 4A,B, Fig. 27). The sandstone overlies the B-marker shale and the basal contact of the sandstone is typically abrupt. In a few cores (e.g. 6-25-49-6W5), the base of the Drayton Valley Member is marked by a cm-thick chert pebble conglomerate which is overlain by argillaceous, bioturbated sandstones (facies 3). No roots or coals are developed at the top of the Drayton Valley Member and the sandstone is abruptly overlain by the A-marker shale (Figs. 24, 27).



(27) Log signature and core description or the proposed type section, Drayton Valley Member, Glauconite Formation. (For legend see p.271)

MODESTE CREEK MEMBER

The term Modeste Creek Member is introduced to describe a thick marine sandstone at the top of the Glauconite Formation which has a sheet-like distribution in the northern part of the study area (Fig. 11). The proposed type section for this unit is the Pan Am Lobstick 6-2-50-6W5 core (Fig. 28). In the type area, this sandstone abruptly overlies the A-marker shale capping the Drayton Valley sandstone (Figs. 24, 28) and consists of 10-25 meters of feldspathic litharenite. This sandstone is generally massive and structureless although low angle convergent laminations and high angle foresets are developed just below the rooted zone in the type section (Fig. 28).

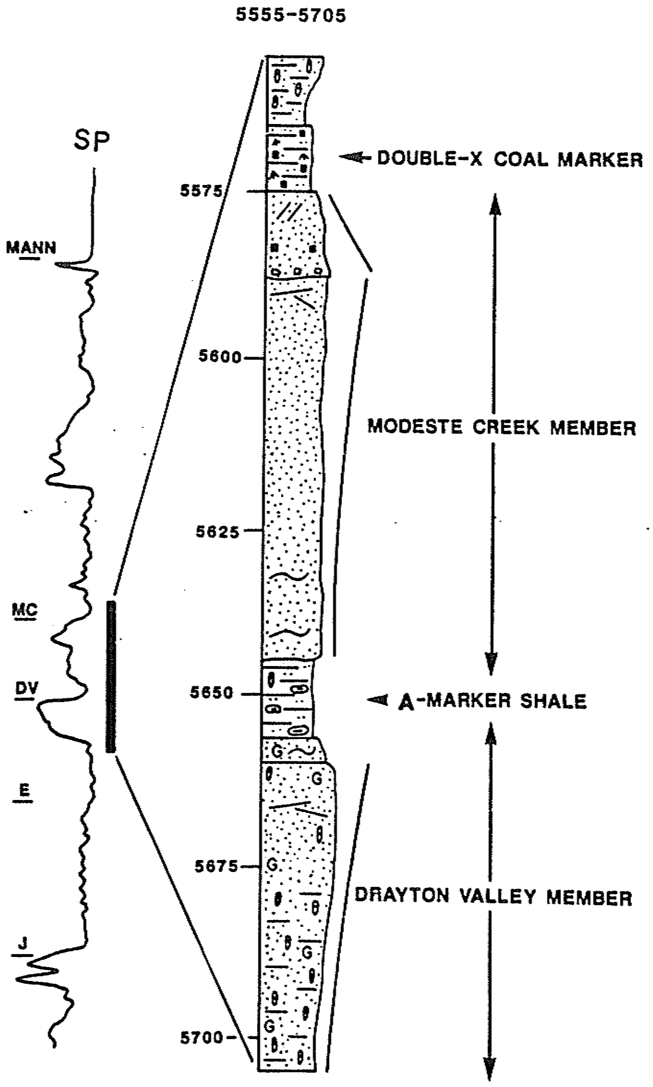
(b) CHANNEL SYSTEMS IN THE GLAUCONITE FORMATION

The marine sandstone and shale sequences in the Glauconite are locally dissected by a series of incised channels. The distribution of the major trends mapped in the study area is shown in Fig. 11. The regional trend on these channels ranges from northeast (Caroline Channel) to northwest (Medicine River Channels) although locally, the channels appear to follow topographic lows on the pre-Cretaceous unconformity. A core showing a typical channel sequence in the Thorsby area is shown in Fig. 29. The sharp (scoured) base of each channel is generally marked by a shale clast breccia and the channels are typically infilled with restricted to non-marine sandstones and mudstones (Facies 7, 8). At least four separate channeling systems are recognized in the Glauconite Formation and the age of these channels, relative to the shale and coal marker beds, is shown schematically in Fig. 24 and described in detail in the following section.

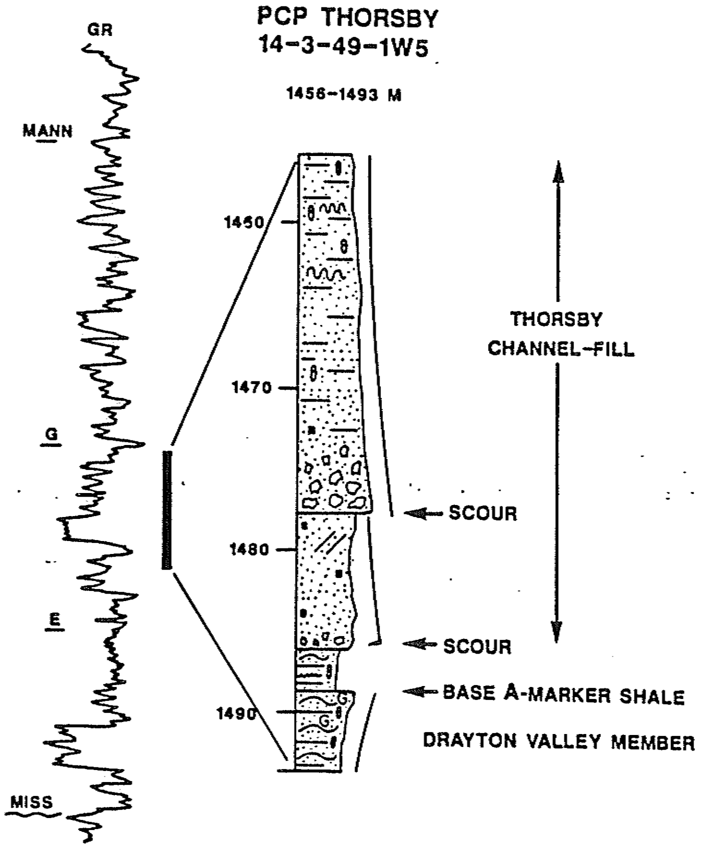
CAROLINE CHANNEL

The oldest channeling event recognized in the Glauconite Formation is found in the the Caroline area (Fig. 11) and a geophysical log section across

TYPE SECTION
MODESTE CREEK MEMBER, GLAUCONITE FORMATION
PAN-AM LOBSTICK 6-2-50-6W5



(28) Log signature and core description for the proposed type section, Modeste Creek Member, Glauconite Formation. (For legend see p.271)



(29) Log signature and core description of typical incised channel sequence, Thorsby area.

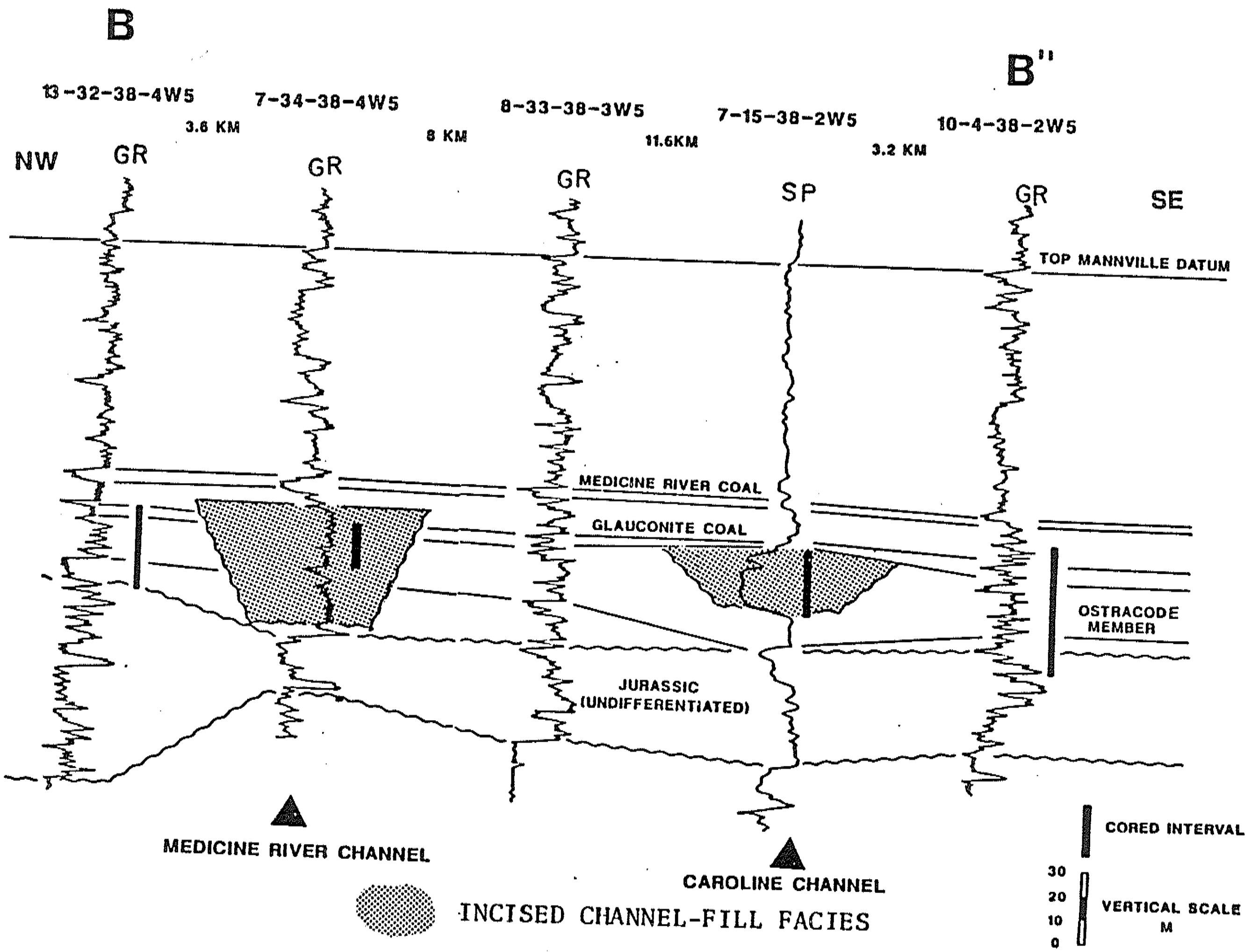
this channel is shown in Fig. 30. This northeast-trending channel cuts through the Glauconite Formation and the underlying Ellerslie interval and is overlain by the B-marker shale and the Glauconite Coal marker. This channel is infilled with mudstones or highly quartzose sandstones (e.g. 7-15-45-2W5).

MEDICINE RIVER CHANNELS

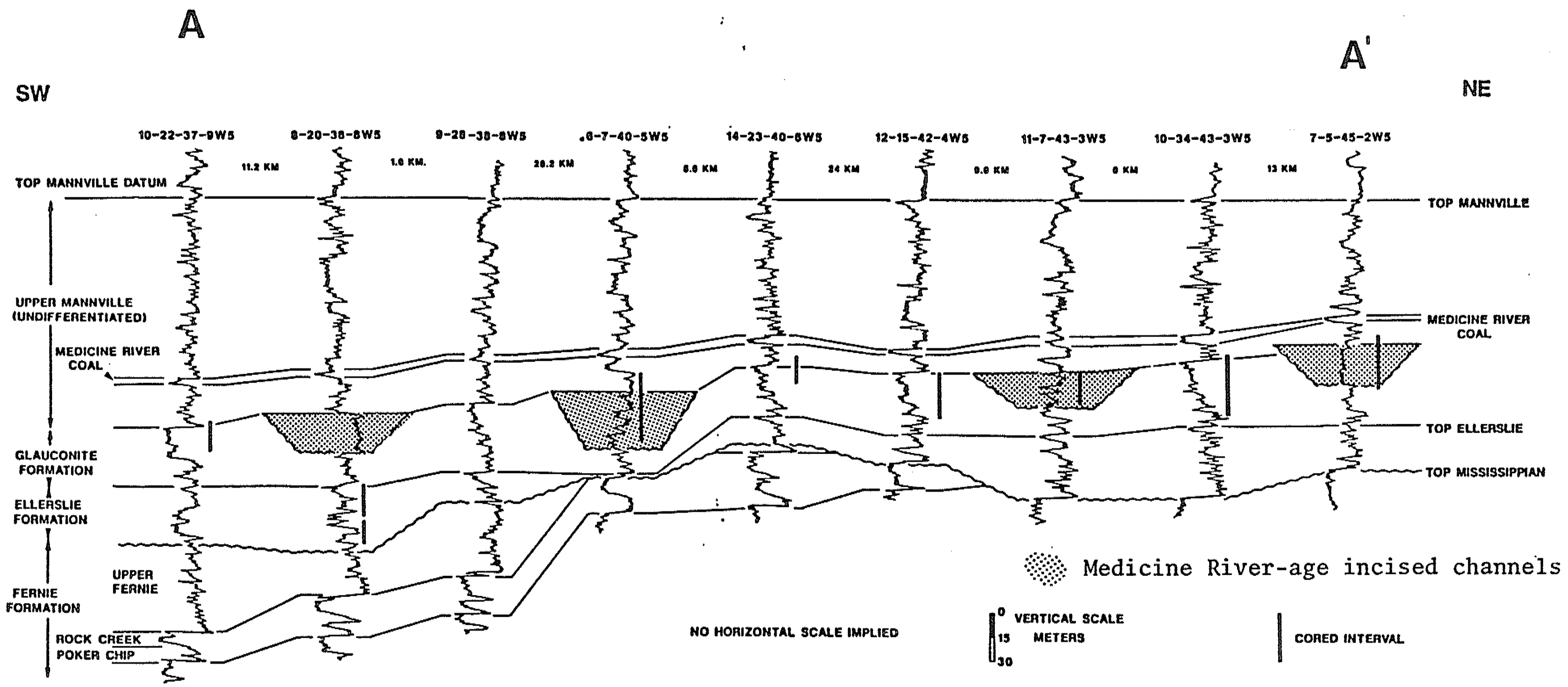
The second channeling event recognized in the study area is represented by the northwest-trending, mud-filled Medicine River channels. These channels cut through, and therefore postdate, the Glauconite Coal and the Medicine River complex (Fig. 30), the Strachan-Hoadley trend (Fig. 31) and the Caroline channel (Fig. 11). These channels were apparently incised and infilled prior to the A-marker transgression and are best developed in the southern part of the study .

THORSBY-PEMBINA CHANNELS

The third stage of channeling is recognized throughout the study area (Thorsby, Pembina, Hoadley and Medicine River areas) and is represented by deeply incised channels which are infilled with feldspathic sandstones. The incision of these channels post-dated deposition of the A-marker shale as well as the overlying Modeste Creek Sandstone and Double-X Coal marker (Fig. 24). In the Thorsby area, several stages of channel incision are recognized as most cores contain at least two shale clast breccia horizons above the A-marker shale (e.g. 14-3-49-1W5, Fig. 29). A log section across this channel (Fig. 32) shows three episodes of channeling with the earliest pre-dating deposition of the A-marker shale (e.g. 7-11-49-1W5) and the other two post-dating the A-marker shale (Figs. 29, 32). Cores from the Pembina area also exhibit several stages of channeling although their relative ages could not be determined with the limited core control in this area.



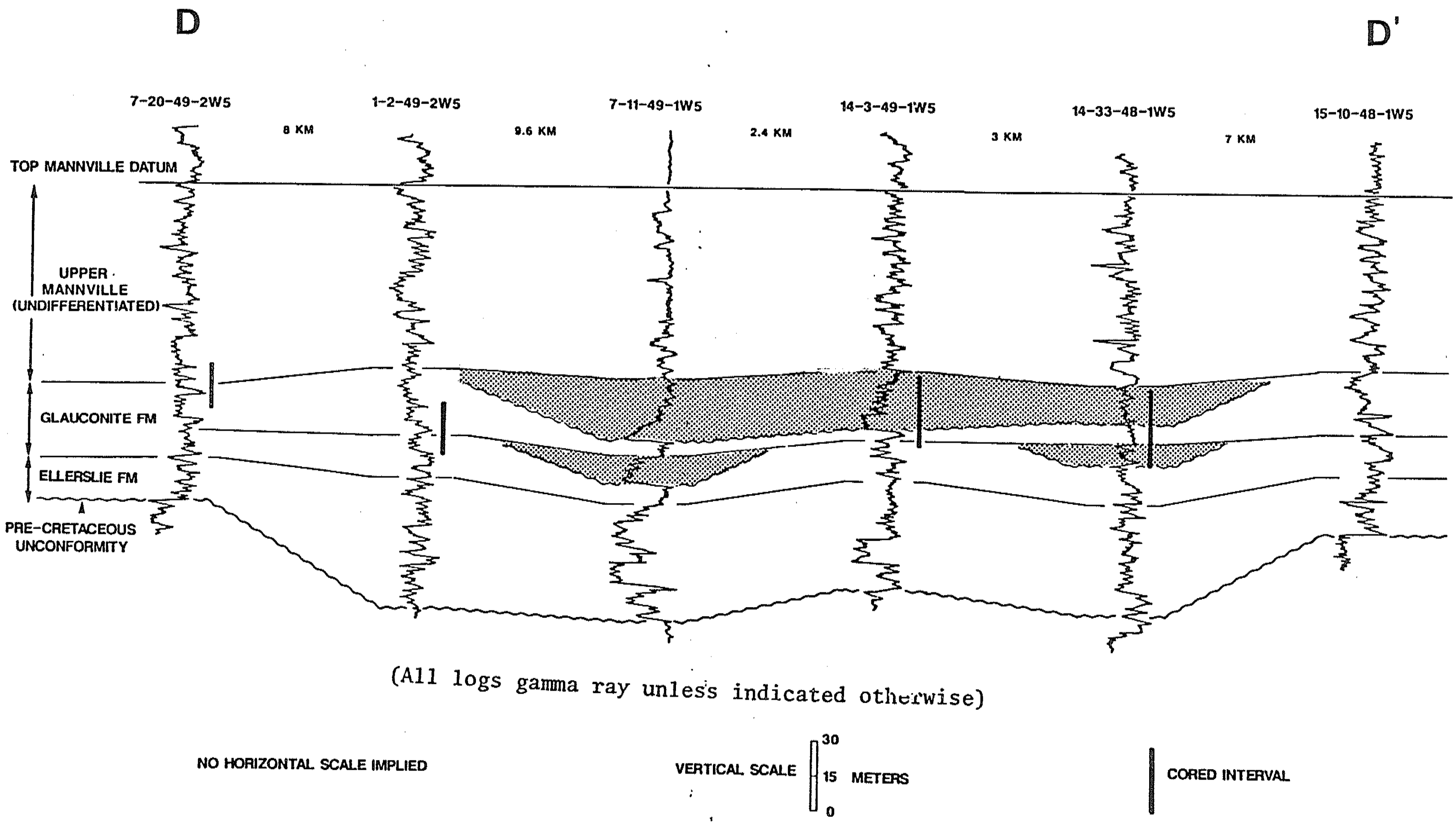
(30) Stratigraphic geophysical log section across the Caroline and Medicine River incised channels, Glauconite Formation.



▨ Medicine River-age incised channels

(All logs are of gamma radiation unless indicated otherwise)

(31) Stratigraphic geophysical log section along strike of the Hoadley-Strachan trend showing contrasting log signature of marine sandstones and conglomerates and incised channel successions.



(All logs gamma ray unless indicated otherwise)

(32) Stratigraphic geophysical log section across the Thorsby incised channel, Glauconite Formation.

EDSON CHANNEL

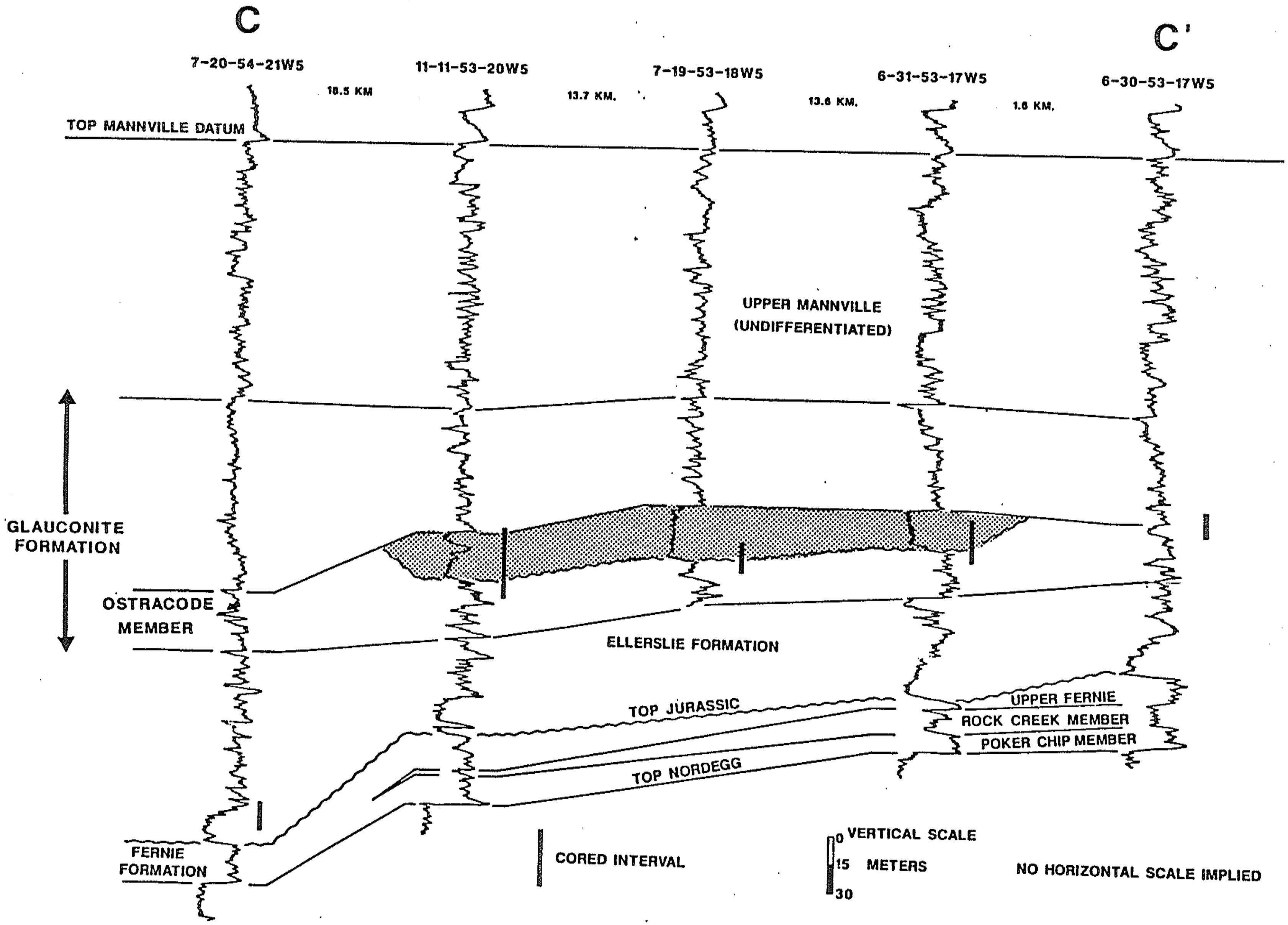
In the Edson area, a prominent northeast-trending channel trend is recognized in the Glauconite Formation (Fig. 11). This channel is probably age-equivalent to the Caroline Channel as it has a similar trend and is infilled with similar (non-feldspathic) sandstones. However, the precise timing of the incision and aggradation of this channel is poorly constrained as the core and log data base in this area is limited and the Ostracode and A and B-marker shales could not be differentiated in this area. A geophysical log section across this channel is shown in Fig. 33. This channel is infilled with either non-bioturbated cross-stratified sandstones (e.g. 7-19-53-18W5) or bioturbated argillaceous sandstone.

(iv) UPPER MANNVILLE IN THE SUBSURFACE

The Upper Mannville section was rarely cored as it does not host any hydrocarbon accumulations in the study area. This interval is probably non-marine as numerous coal horizons are recognizable on geophysical logs and the interval contains several sharp-based fining-upward sequences which are probably fluvial sandstones. These sequences develop at approximately the same stratigraphic interval in adjacent wells and the thickest, and most consistent, of these log-defined channeling events is developed at the top of the Mannville section, directly below the Joli Fou shale. The only core of this sandstone in the study area (i.e. 9-6-48-6W5) consisted of non-bioturbated, cross-stratified feldspathic litharenites (Facies 8C) overlain by non-marine (clay-plug) mudstones (facies 6).

(C) STRATIGRAPHIC RELATIONSHIPS BETWEEN THE EARLY CRETACEOUS IN OUTCROP AND SUBSURFACE

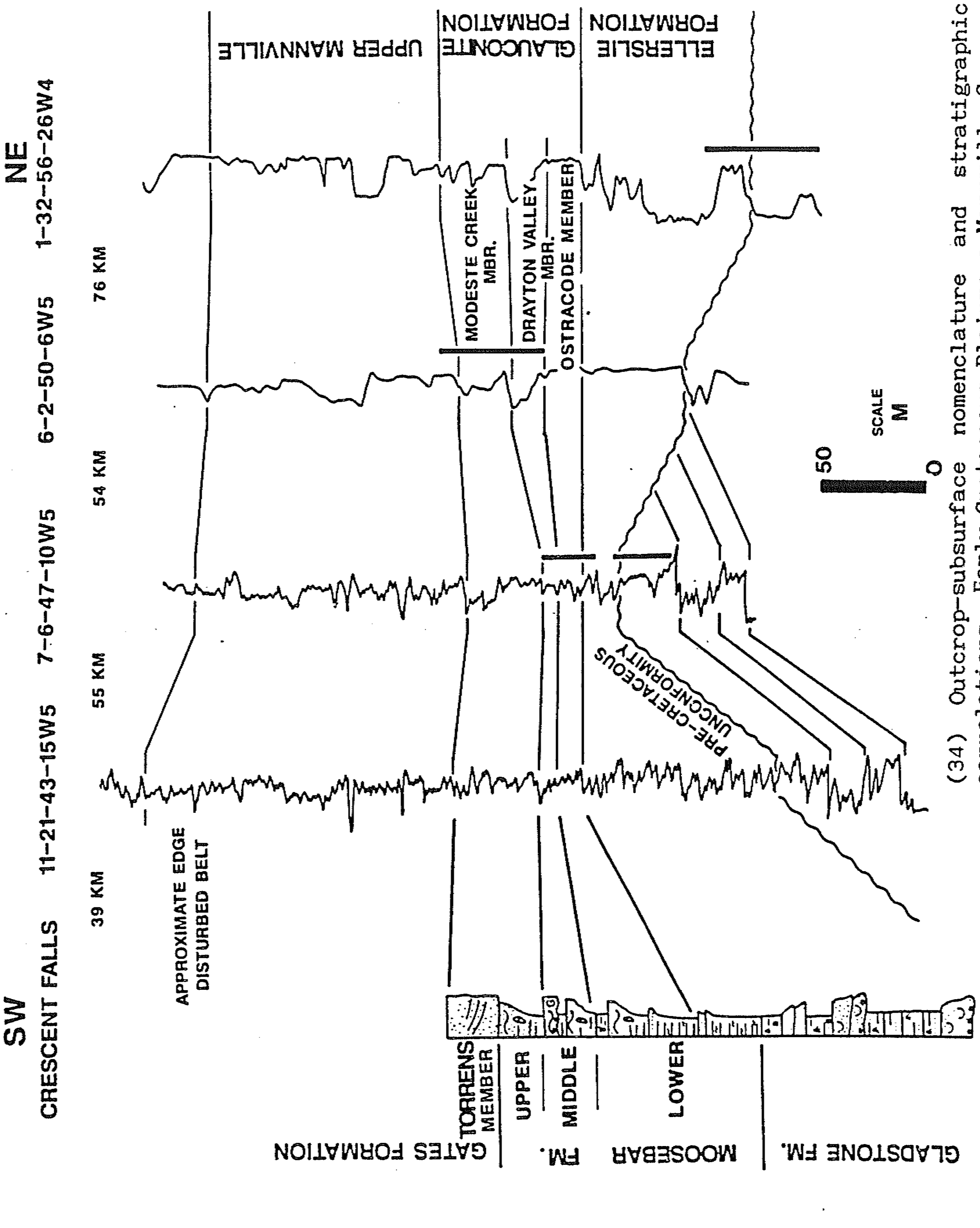
The stratigraphic relationship between the Early Cretaceous strata in the Blairmore and Luscar Groups in the Foothills and the Mannville Group of the



(33) Stratigraphic geophysical log section across the Edson Channel.

(all logs are gamma ray unless indicated otherwise) western Plains has not been clearly established. Previous workers (e.g., Mellon 1967; McLean and Wall 1981) correlated the Cadomin and lower (non-marine) part of the Gladstone with the Ellerslie Formation, the Calcareous Member of the Gladstone with the Ostracode Limestone, and the Moosebar Formation with the Glauconite Formation (Fig. 8). While these correlations outline approximate stratigraphic relationships, they do not recognize the complex cyclicity developed in the Moosebar-Glauonite intervals and are thus of limited use for resolving detailed depositional history of this interval. To illustrate the Foothills-Plains correlations proposed in this thesis, a cross section was constructed between the Crescent Falls section in the Foothills and a series of key wells in the west-central Plains (Fig. 34).

The correlations outlined in Fig. 34 indicate that the non-marine Gladstone Formation (and underlying Cadomin which is not exposed in the Crescent Falls outcrop) are equivalent to the lower (non-marine) part of the Ellerslie Formation in the Plains. The shales at the base of the lower Moosebar are correlated with the brackish-restricted marine strata at the top of the Ellerslie and the bioclastic shales in the middle of the lower Moosebar are correlated with the Ostracode Member of the Glauconite Formation in the subsurface. These bioclastic shales both contain the distinctive Metacypris persulcata ostracode assemblage. However, since the same assemblage was found in the Ellerslie shales in the western Plains (SH-7, Table 6), it does not appear to constitute a useful biostratigraphic marker. A similar interpretation was forwarded by Finger (1983) who noted that this assemblage is comprised of long-ranging species and that its distribution was probably controlled by environmental conditions. The presence of this assemblage is cited here only as evidence that the Lower Moosebar, Ellerslie and Ostracode intervals were all deposited under similar (brackish-water) conditions.



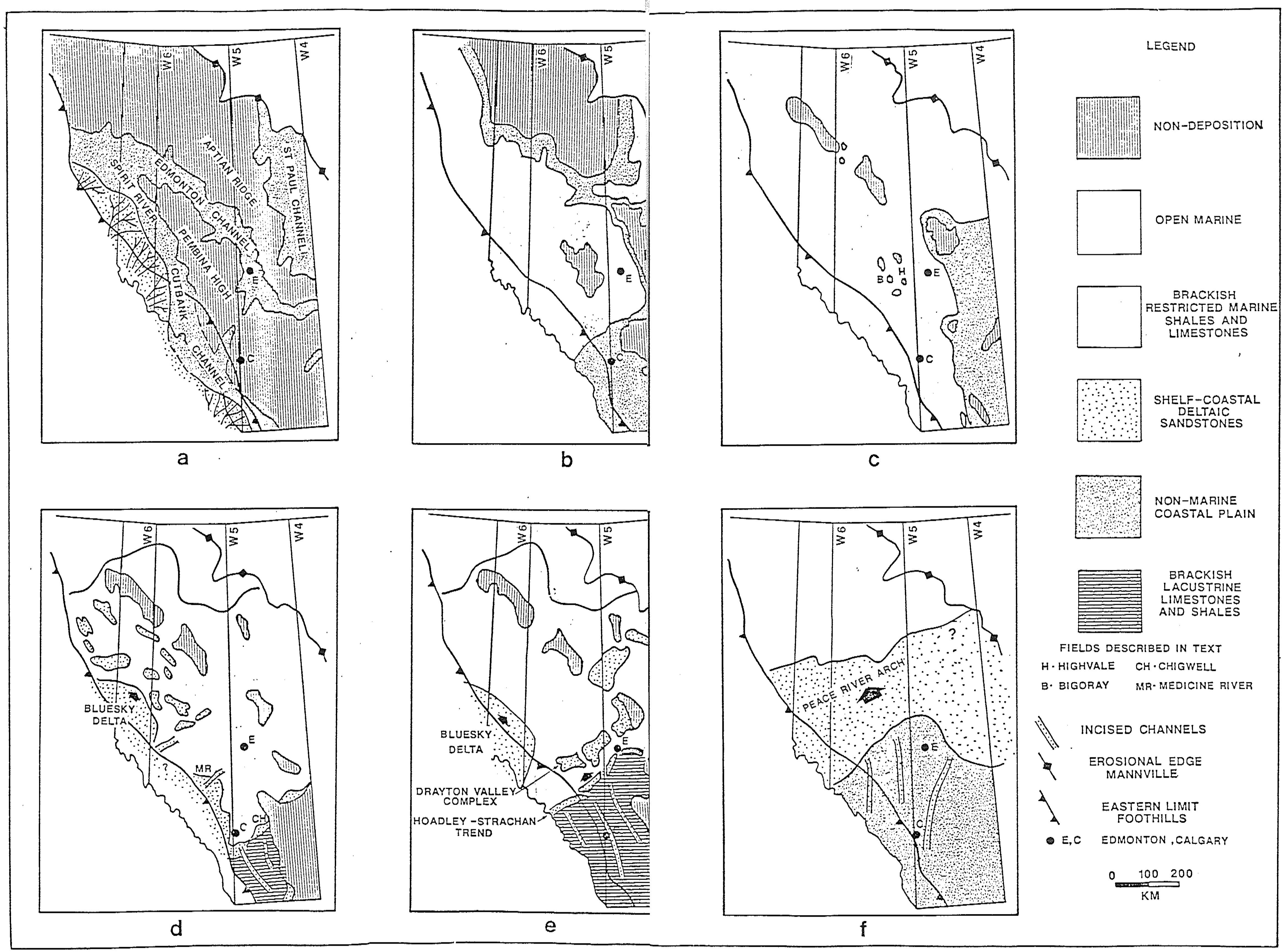
(34) Outcrop-subsurface nomenclature and stratigraphic correlations, Early Cretaceous Blairmore-Mannville Groups west central Alberta.

The quartzose sandstone at the top of the lower Moosebar is correlated with the Medicine River Member (Glauconite Formation) in the Plains. The coal-capped regressive marine sandstones in the Fall Creek section, and the marine conglomerates in the Tay River section (middle Moosebar) are correlated, and are on depositional strike with, the marine sandstones and conglomerates comprising the Hoadley-Strachan trend in the subsurface (Fig. 11). The glauconitic "upper twin" sandstone (middle Moosebar) in the Crescent Falls section is correlated with the Drayton Valley Member of the Glauconite Formation in the Plains. The upper Moosebar shale, and overlying marine sandstone (Torrens Member, Gates Formation) in the Foothills is correlated with the Glauconite-A shale and overlying Modeste Creek Member (Glauconite Formation) in the Plains. The feldspathic sandstones in the Ram River section are correlated with the feldspathic Beaver Mines of the southern Foothills and Thorsby-Pembina channel sandstones in the Plains (Fig. 34).

(D) EARLY CRETACEOUS DEPOSITIONAL HISTORY AND PALEOGEOGRAPHY

The revised stratigraphic correlations presented in this thesis provide an improved stratigraphic framework for resolving the detailed depositional history of the Early Cretaceous succession in western Canada. The outcrop and subsurface data compiled in the thesis was integrated with paleogeographic maps published by Jackson (1984) to "tie into" depositional trends recognized within the succession in other parts of the basin. The Blairmore-Luscar-Mannville strata of western Alberta can be interpreted in terms of six distinct depositional events and paleogeographic maps for each of these events are shown in Fig. 35.

(i) The unconformity at the base of the Early Cretaceous interval records a



(35) Summary of geologic history and evolving paleogeography of the Alberta Basin during the Early Cretaceous.

major episode of uplift, tilting and erosion which affected the entire Western Canadian Sedimentary Basin. The origin and tectonic significance of this unconformity is discussed in more detail in Chapter 11. In the Foothills, the overlying Cadomin conglomerate is interpreted as a braided river or humid alluvial fan deposit which overlies a pediment surface (McLean 1977; Schultheis and Mountjoy 1978). Paleocurrent data, isopach maps and plots of maximum pebble size in the conglomerate indicate that the paleoslope dipped northeasterly, away from the uplifting Cordillera (Fig. 36A). The sharp-based channel sandstones in the overlying Gladstone Formation are interpreted as point-bar deposits which were deposited by northwest-flowing river systems which followed Spirit River Channel and debouched into the Gething Delta of northeastern British Columbia (Stott 1984). The Cadomin-Gladstone interval thins eastward and pinches out along the crest of the Pembina High (Fig. 35A). The basal Ellerslie strata in the Edmonton Channel is probably equivalent to the Cadomin-Gladstone interval although the age and sedimentology of these strata have not been well documented.

(ii) The second stage of Early Cretaceous sedimentation records a major southward incursion of the Moosebar-Clearwater Sea into the elongate foreland basin (Fig. 35B). This transgression is represented by the brackish to freshwater strata in the basal lower Moosebar in the Foothills and the upper Ellerslie in the Plains. Across the western Plains, this interval is generally less than 30m thick although it thickens to more than 60m in some outcrops in the western Foothills (e.g. Crescent Falls) where thrust-induced subsidence rates would have been greater. The geographic limits of this transgression are poorly constrained in the western plains although brackish-water facies are recognized throughout the study area and across the Edmonton Channel in the east (Banerjee 1986). It is not clear whether sandy shoreline-delta systems were developed along the margins of this seaway although porous sandstones are developed in this interval in the Edmonton "Channel" (Banerjee 1986) and around the margins of a series of small emergent islands (e.g. Highvale, Pembina, and Bigoray fields) along the axis of the Pembina High (Fig. 35B).

(iii) Continued transgression of the Early Albian Clearwater-Moosebar Sea (Fig. 35B) led to the deposition of a northwestward-thickening interval of brackish-marine strata in western Alberta. At maximum transgression, this sea blanketed most of southwestern Alberta (Fig. 35C) although a few small "islands" along the crest of the Pembina High may have remained emergent at this stage. This transgression is represented by the bioclastic shales in the lower Moosebar and similar lithofacies in the equivalent Ostracode Member in the central Plains (Fig. 35B). The presence of abundant synaerisis cracks, ubiquitous wave-ripple lamination, a low density-low diversity trace fossil assemblage, and a brackish to freshwater microfossil assemblage records deposition in a shallow semi-restricted basin which was subjected to periods of fluctuating salinity. The cause of these salinity fluctuations could not be established although it is possible that they record either climatically or seasonally-controlled changes in freshwater input or basin circulation patterns.

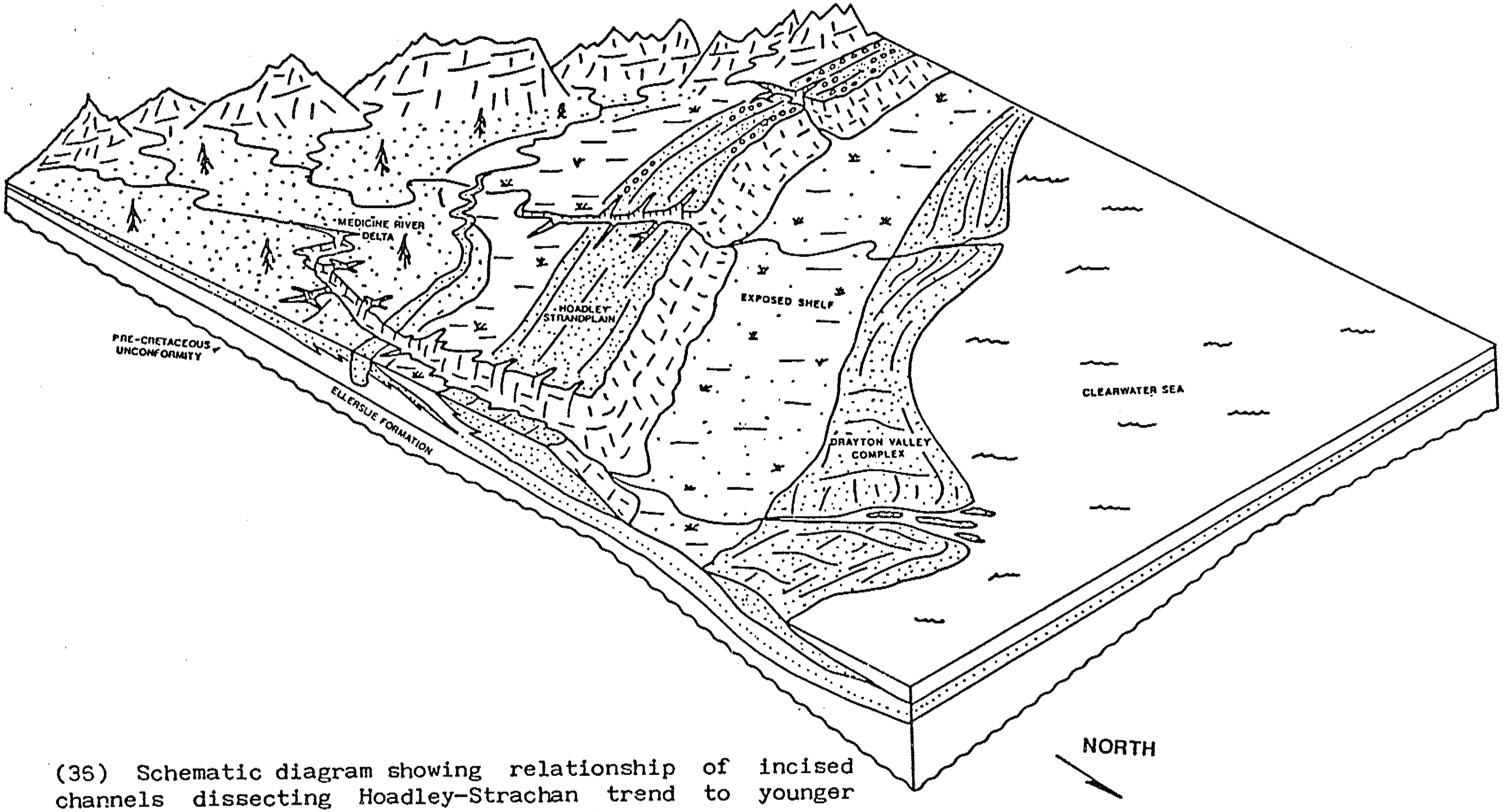
(iv) The strata overlying the bioclastic shales is comprised of a series of diachronous, northward-offlapping regressive marine sandstones, separated by thin transgressive marine shales, which are locally dissected by deeply-incised fluvial -estuarine channels. These sandstones record episodic fluctuations in relative sea level which ultimately resulted in the retreat of the Moosebar-Clearwater sea from this part of the foreland basin. In southern Alberta, these fluctuations in relative sea level are represented by a series of deep, narrow channels which were incised during a drop in sea level and aggraded during a subsequent rise in sea level (D.James pers.comm. 1987). Although the exact correlations between the incised channels of the southern Plains and the regressive marine sandstones in central Alberta have not been established, a series of hypothetical reconstructions is shown in Figs. 35 D,E and F.

The initial retreat of the Clearwater Sea resulted in deposition of the thin, coal-capped quartzose marine sandstone at the top of the lower Moosebar in the Foothills, and the equivalent Medicine River sandstone in the western Plains (Fig. 35D). This sandstone comprises the reservoir in the Chigwell and Medicine River fields and probably correlates with the Home Sandstone of the Turner Valley area (Mellon 1967) and the Bluesky Sandstone in northern Aberta (Jackson 1984). The clean, well-sorted texture and abundance of wave-lamination and hummocky cross-stratification in these marine sandstones records a strong storm/wave influence in the basin during their deposition. In southern Alberta, this regressive event is marked by the bioclastic limestones capping the Calcareous Member-Ostracode interval. If this correlation is correct, it suggests that the limestones were deposited in some type of lagoon or bay, developed south (landward) of a sandy shoreline-delta complex developed in central Alberta.

In the Medicine River area, the trend of the (incised) Caroline channel suggests that local paleoslope dipped to the northeast during this initial regression. The aggradation (infilling) of the Caroline channel probably occurred in response to a rise in sea level which culminated with the overlying middle Moosebar (B-marker shale) transgression.

(v) A subsequant advance of the Clearwater Sea led to deposition of the middle Moosebar shale in the central Foothills and the B-marker shale in the western Plains. A barrier island complex developed along the south margin of the Hoadley-Strachan Complex. During the ensuing regression, this barrier island evolved into a regressive, wave-dominated shoreline-delta system. The Hoadley Member, and equivalent sandstones and conglomerates in the middle Moosebar in the Fall Creek and Tay River sections, record approximately 15-20km of seaward progradation of this complex. An excellent modern analog for this progradation is the Costa de Nayarait in Mexico (Curray et al. 1969) which has prograded seaward as a shoreline-attached strandplain. The northeast elongation of the Hoadley-Strachan Complex demonstrates that this regression was accompanied by a pronounced change in basin geometry as paleoslope had shifted 90 degrees to the northwest (Fig. 35E). The presence of a second rooted horizon in the middle of the Hoadley interval in a few cores (e.g. 9-3-45-2W5) indicates that, at least locally, the Hoadley trend represents a stacked regressive marine sequence. The thick Glauconite Coal which blankets both the Medicine River and Hoadley areas indicates that an areally extensive raised swamp developed when this area became emergent.

The linear Hoadley-Strachan trend is dissected by numerous northwest-trending incised channels which apparently record a dramatic drop in relative sea level. This apparently resulted in the rapid northward progradation of the shoreline and establishment of a younger (lowstand) shoreline in the Drayton Valley area (Fig. 35E). A schematic diagram showing the basin configuration during this lowstand is shown in Fig. 36. The sharp, pebbly basal contact of the Drayton Valley sandstone with the underlying marine shales confirms that the sand was transported onto the shelf during a



(35) Schematic diagram showing relationship of incised channels dissecting Hoadley-Strachan trend to younger (lowstand) shoreline in the Drayton Valley area.

pronounced drop in relative sea level. Although the Drayton Valley Complex does not extend into the disturbed belt (Fig. 11), the glauconitic sandstone underlain by chert pebble/cobble conglomerate in the Ruby Creek and Crescent Falls sections was probably deposited by the same depositional event. A subsequent rise in relative sea level resulted in the inundation of this (lowstand) shoreline and reworking by shallow marine processes to form some type of shelf sand ridge complex.

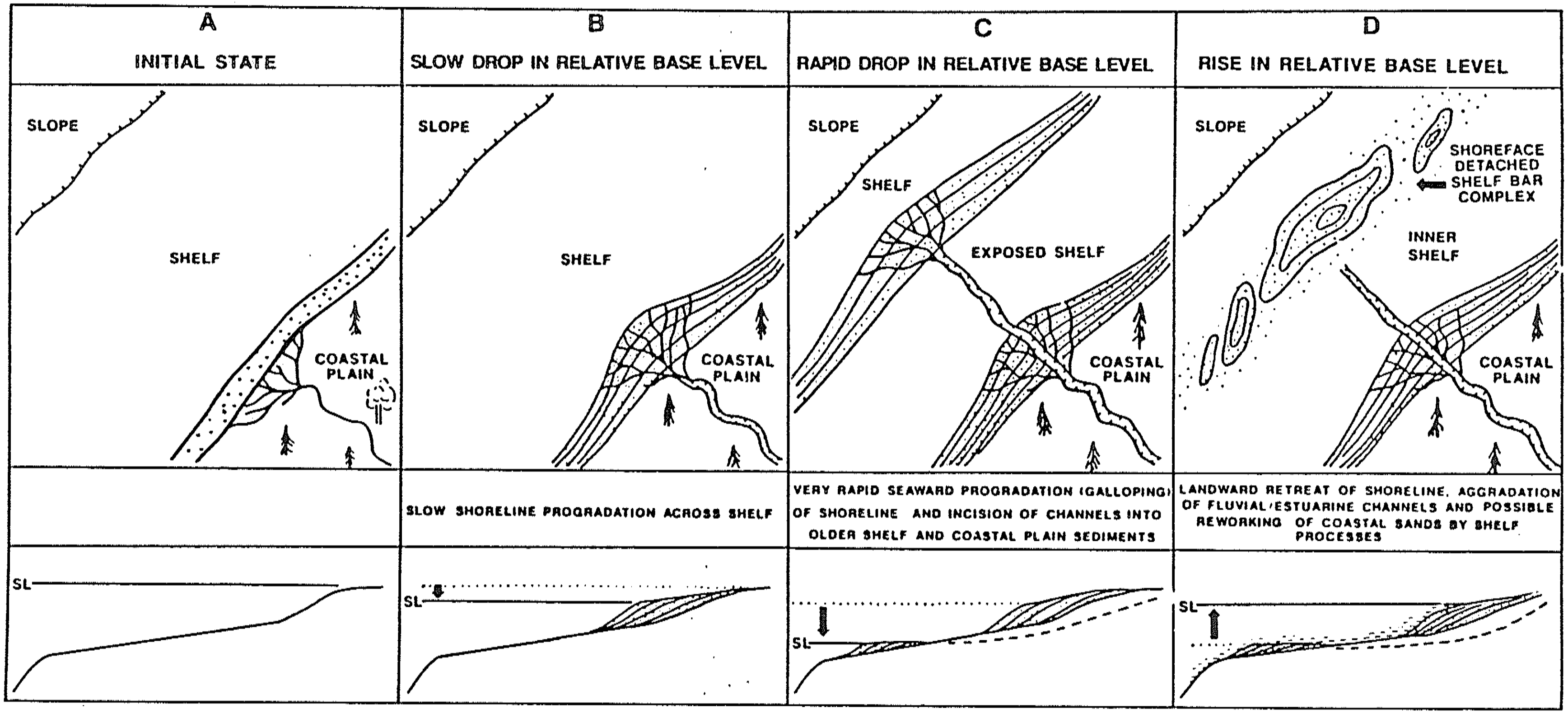
(vi) The final major advance of the Clearwater Sea into central Alberta deposited the upper Moosebar shale in the Foothills and the A-marker shale (Glauconite Formation) in the Plains. In the Foothills, this shale is not developed south of Nordegg and appears to have pinched out against the seaward margin of the Hoadley-Strachan Complex. The subsequent regression of this sea is recorded by the thick sheet-like feldspathic marine sandstones comprising the Torrens Member in the Foothills and the equivalent Modeste Creek sandstone in the Plains. This regression was followed by another dramatic drop in relative sea level which initiated the third channeling event recognized in the study area. This channeling post-dated deposition of the Upper Moosebar-Glauconite-A shales and is represented by the Pembina and Thorsby channels in the subsurface and the Beaver Mines Channels in the Foothills (e.g. Ram River section). The petrographic similarity of the Torrens and Modeste Creek marine sandstones with the Beaver Mines sandstones in southern Foothills (Chapter 7) suggests that the Beaver Mines-age river systems were supplying volcanic-rich detritus from a southern Cordilleran source to this prograding shoreline-delta complex in central Alberta(Fig. 35F).

The top of the Modeste Creek-Torrens sandstone records the end of marine sedimentation in central Alberta as the overlying Upper Mannville-Gates interval consists of non-marine coal-bearing sandstones and mudstones. During this time (Middle Albian), the locus of marginal marine sedimentation shifted northward to the Peace River Arch (Fig. 35F) where regressive marine sandstones and conglomerates of the Falher-Gates Formation were deposited (Leckie and Walker 1982).

(E) A DEPOSITIONAL MODEL

The three transgressive-regressive successions recognized in the Moosebar-Glauconite interval record the episodic advance, and subsequent retreat of the Clearwater Sea in central Alberta. Each succession is comprised of a basal (transgressive) marine shale overlain by a regressive (coal-capped) marine sandstone and is locally dissected by incised fluvial-estuarine channels. A depositional model which explains the stratigraphic distribution of all three elements of this succession is shown in Fig. 37 and is discussed in the following section.

The thin transgressive shale at the base of each succession records mud deposition on a shallow shelf during a rise in relative sea level (Fig. 37A). A subsequant drop in relative sea level, or increase in sediment supply, initiates seaward progradation of the shoreline and deposition of a thick regressive marine shoreline-delta sandstone (Fig. 37B). An ensuing drop in relative sea level results in very rapid progradation of the coastline across the shelf and incision of fluvial channels into previously deposited strata. During this drop in sea level, a younger (lowstand) shoreline is established at some point landward of the original shoreline (Fig. 37C). During a subsequant rise in relative sea level, the lowstand shoreline deposit is transgressed and the previously incised channels aggrade with sediment. Any coals or roots at the top of the lowstand shoreline are removed during shoreface retreat



(37) Depositional model proposed for the Early Cretaceous strata in the Alberta Basin.

(Nummedal and Swift 1987) and the sand body is reworked by shallow marine processes to form an offshore sand ridge complex (Fig. 37D). A Holocene analog for this type of sand ridge complex is present on the storm-dominated Atlantic shelf where transgression of a coastal depocenter has led to preservation of thick sandstones in a mid shelf setting (Swift et al. 1973). A similar model has been proposed by Plint and Walker (1987) to explain the distribution of thick shelf sandstones and conglomerates in the Late Cretaceous Cardium Formation in western Alberta.

CHAPTER 7 FRAMEWORK COMPOSITION AND MAJOR ELEMENT CHEMICAL COMPOSITION

For more than a century, sedimentary petrologists have understood in a qualitative sense that the framework composition of sandstones was related to the type of rocks exposed in the source area. This chapter will open with a discussion of the provenance interpretations previously forwarded for the Jurassic-Early Cretaceous sandstones in Alberta. The remainder of the chapter will focus on the documentation and interpretation of the framework composition of these sandstones.

(A) PREVIOUS WORK

Significant variations in the framework composition of Jurassic-Early Cretaceous sandstones have been reported by previous workers including Glaister (1959), Williams (1963), Rapson (1965), Mellon (1967), Vigrass (1977), Schultheis and Mountjoy (1978), Hopkins (1981), Putnam and Pedskalny (1983), and Leckie (1985). It is difficult to compare these data directly as the specific stratigraphic interval examined, the type and location of samples (outcrop or subsurface) and the methodology employed was different for each of these studies. In a regional sense, however, three distinct framework assemblages could be differentiated in the Jurassic and Early Cretaceous wedge in Alberta and each of these is summarized below.

(1) The Middle Jurassic (Rock Creek-Sawtooth) and basal Late Jurassic (Swift) sandstones) are highly quartzose, very well-sorted, and contain only traces of chert and feldspar. These sandstones are probably multicyclic in origin and were initially derived from the exposed Canadian Shield to the east (Springer et al. 1964; Marion 1984; Poulton 1984).

(2) In the southern Foothills, the uppermost Jurassic-Early Cretaceous Kootenay-Nikanassin sandstones, and the basal part of the overlying Blairmore Group (Cadomin and Gladstone Formations) are quartz and chert-rich and virtually devoid of feldspar and igneous and metamorphic rock fragments. These sandstones contain an ultrastable heavy mineral assemblage and were probably reworked from uplifted Proterozoic, Paleozoic and Early Mesozoic sedimentary rocks exposed in a foreland fold-thrust belt flanking the ancestral Cordillera (Rapson 1965; Mellon 1967; Schultheis and Mountjoy 1978; and Poulton 1984).

In the western Plains, the Kootenay-Nikanassin is largely eroded and where present, has not been studied from a petrographic perspective (Springer et al. 1964). The strata equivalent to the Cadomin-Gladstone interval in the Plains (Ellerslie-McMurray-Dina-Basal Quartz Formations) are typically fine-grained and highly quartzose and their provenance is controversial. Williams (1963), Rudkin (1964) and Hopkins (1981) suggested that the quartz sand was derived from an Eastern (Shield) source whereas others (McGookey et al. 1972; Christopher 1975) have proposed that northwest-flowing river streams drained a Western Interior source area which extended as far south as New Mexico.

(3) Sandstones in the upper part of the Blairmore and Mannville Groups throughout Alberta and Saskatchewan are highly feldspathic and contain abundant volcanic rock fragments, chert and quartz and a metastable heavy mineral assemblage (Glaister 1959; Williams 1963; Rapson; 1965; Mellon 1967; and Putnam and Pedskalny 1983). The basal contact of the feldspathic interval is typically sharp, particularly in southern Alberta, and this appears to mark an abrupt change in provenance (Mellon 1967; Vigrass 1977). The proportion of volcanically-derived material in the Upper Blairmore-Mannville sandstones is greatest in the southern Foothills and appears to decrease to the north and

east. As an example, feldspar comprises an average of 15.5% of the framework of Beaver Mines sandstones in the southern Foothills (Mellon 1967) and only 4.3% of the framework of equivalent Gates sandstones in the northern Foothills (Leckie 1985). Volcanic rock fragments are also more abundant in the southern Foothills although it is difficult to compare these data directly as Mellon (1967) and Leckie (1985) employed different lithic fragment classification schemes. In eastern Alberta, the feldspathic (westerly-derived) and quartzose (easterly-derived) sandstones are interbedded in the Upper Mannville interval (Vigrass 1977).

(B) METHODOLOGY EMPLOYED IN THIS STUDY

To complement the petrographic work completed by the researchers described above, 106 thin sections were cut from core and outcrop samples of Jurassic and Early Cretaceous sandstones in west-central Alberta. Each thin section was impregnated with blue-dyed epoxy resin and stained for feldspar using a technique introduced by Houghton (1980). Two hundred grains were counted in each slide along 8 traverses which included 25 grains/traverse. These data are tabulated in Appendix 4, summarized in Table 7, and plotted in Figs. 38-46. Porosity was also tabulated in this count (Appendix 4) although it appears that extensive plucking had occurred during the preparation of thin sections as some of the samples have much higher count porosity than was recognized when they were examined with a binocular microscope. The framework data collected in the first count were plotted on QFL plots proposed by Folk (1980) and rock names were assigned to each of the stratigraphic units. On these plots, the chert population, as well as the polycrystalline quartz grains, were assigned to the L (lithic fragment) pole and the Q (quartz) pole included only monocrystalline quartz grains. The framework composition of eleven representative samples was

Stratigraphic Unit	Q		Feldspar			Lithics			%	Glauconite		Cement		Folk		
# of Samples	Qm	Qp	P	K	?	Chert	Carb.	L?	Frame Work	Grains	Opaque	+ Matrix	ϕ	Q	F	L
*Beaver Mines n = 2	16.5	7.5	10.5	-	19.0	21.0	0.5	14.0	89	-	2.5	7.5	1.0	27	32	41
*Torrens Mbr, Gates Fm n = 4	16.0	7.0	4.8	-	19.0	18.8	-	9.8	75.3	1.1	0.6	19.8	3.4	31	32	37
Modeste Creek Mbr n = 5	17.2	5.2	1.6	-	15.6	13.4	2.2	13.4	68.8	1.2	2.4	18.2	9.4	33	25	42
* Middle Moosebar n = 7	37.6	3.8	0.5	-	2.0	18.2	6.7	6.8	75.6	9.3	1.2	12.3	1.6	54	3	43
Hoadley Mbr n = 12	47.9	6.9	0.1	0.0	1.7	15.3	0.7	8.5	81.1	4.8	1.9	4.0	7.9	67	2	31
Drayton Valley Mbr n = 6	33.8	7.2	1.2	-	4.5	21.5	0.3	12.3	80.8	3.3	1.1	4.4	10.5	51	7	42
*Lower Moosebar n = 1	98.0	1.0	-	-	-	1.0	-	-	100	-	<1.0	-	-	99	0	1
Medicine River Mbr n = 2	84.5	1.5	-	-	-	3.5	-	0.5	90	-	1.0	0.5	8.5	96	0	4
* Gladstone Fm n = 6	24.3	7.8	-	-	-	28.5	6.0	11.5	78.2	-	1.3	17.8	2.7	42	0	58
Ellerslie Fm n = 18	54.2	3.9	<.1	-	.1	16.3	0.4	2.7	77.7	-	1.5	10.7	10.1	75	0	25
*Kootenay-Nikanassin n = 7	38.8	2.6	-	-	-	29.3	3.0	2.4	76.1	0.3	1.3	22.2	-	53	0	47
Fernie - Fm n = 14	75.4	5.1	-	-	-	3.5	-	0.40	84.4	1.2	0.8	6.9	6.4	95	0	5

Table 7: Summary of Framework Composition of Jurassic and Cretaceous Sandstones West Central Alberta
(Grouped Into Outcrop Stratigraphic Units & Their Subsurface Equivalents)

* Outcrop samples

recalculated (Table 8), using Dickinson and Suczek's (1979) parameters, and plotted on their QFL and QmFLt diagrams (Fig. 45) to evaluate the provenance of the detritus.

After the initial (framework) count was completed, a smaller number of samples were selected for detailed analysis of the quartz, feldspar and rock fragment population. The second count was designed to compare the crystallinity and degree of undulosity of the quartz population and to interpret the provenance of the clastic detritus, based on comparison with studies of unconsolidated sands presented by Basu et al. (1975). Eleven medium-grained sandstones were examined and 100 quartz grains were analyzed from each of these samples (Table 9, Fig. 46).

The third and fourth counts focused on the feldspar and rock fragment population respectively (Tables 10 and 11). As identification of these components was difficult in the fine to very-fine grained samples, only medium-grained samples were examined.

(i) PROBLEMS OF PETROGRAPHIC ANALYSIS

Most of the Cretaceous sandstones contained significant amounts of clay, either as matrix or cement, and it was very difficult to differentiate these components from squashed lithic grains and highly altered, sericitized feldspars in thin section. In addition, most of the quartz grains exhibited varying degrees of quartz overgrowths and, in most grains, the margin of the original detrital grain with the overgrowth could not be readily discerned. To introduce some consistency into the point-counting process, only clearly identifiable rock fragments were included as framework and any clay-carbonate material without distinct grain boundaries was counted as undifferentiated clay cement-matrix. Quartz overgrowths were counted as part of the framework grains.

These arbitrary designations would exaggerate the quartz/lithic ratio but are considered to be the only consistent manner of evaluating the modal composition of the clay cement and matrix-rich sandstones which contained abundant quartz overgrowths.

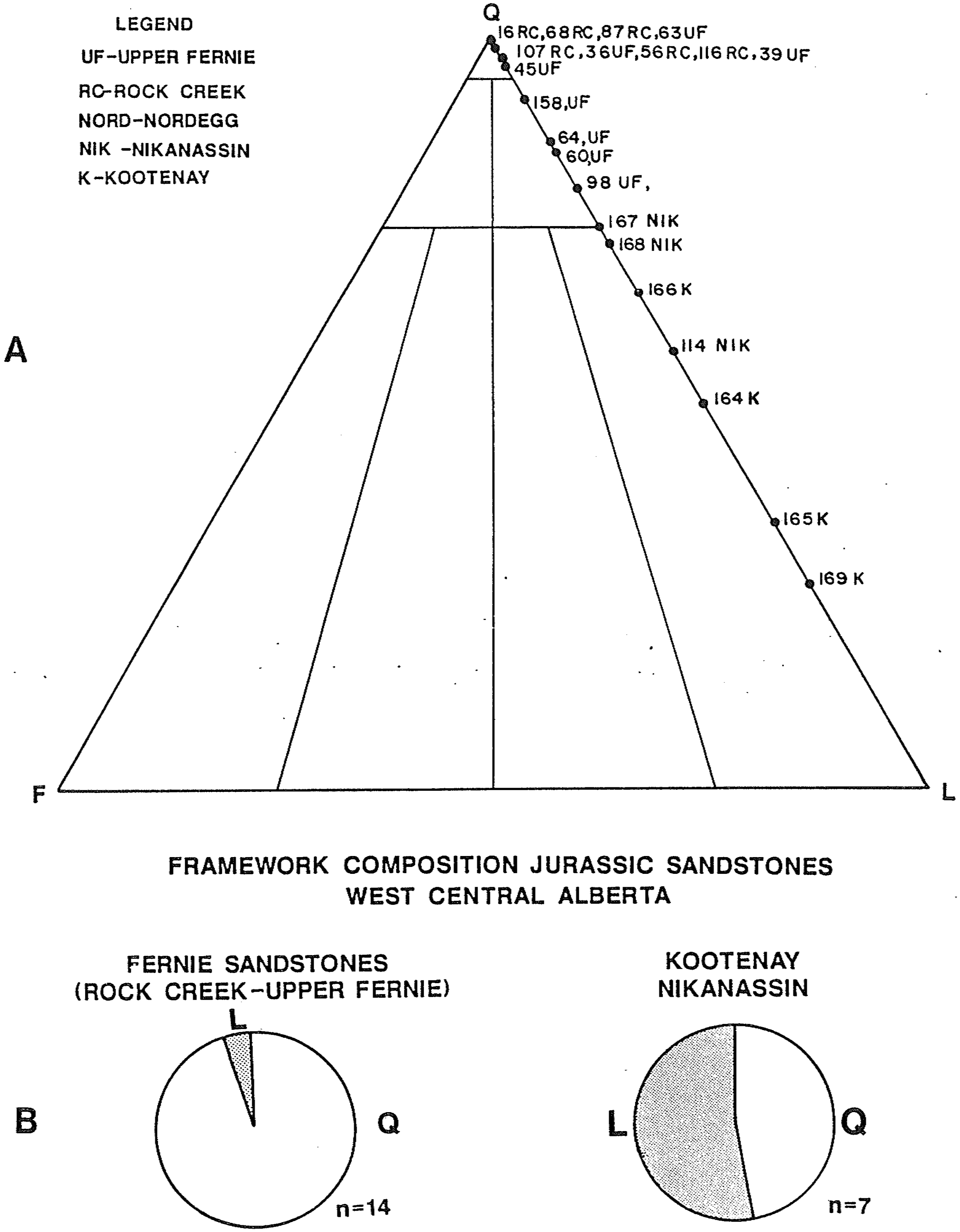
(C) STRATIGRAPHIC VARIATIONS IN FRAMEWORK COMPOSITION

When the framework composition data from all of the samples were compiled (Table 7), systematic variations in the framework composition of the Jurassic and Early Cretaceous sandstones were recognized. The petrography of each stratigraphic unit will be described in the following section and the implications of this on outcrop-subsurface correlations and changing provenance of the detritus, will be presented in a separate section at the end of this chapter.

(i) FERNIE SANDSTONES

Fourteen samples of Fernie sandstones were point counted and these data are tabulated in Appendix 4A, summarized in Table 7 and plotted on the QFL plot in Fig. 38A). These sandstones are typically very fine to fine-grained, well sorted, highly quartzose and extensively cemented by quartz overgrowths. Most of the Jurassic sandstones have a low clay-cement matrix content and recognizable framework grains (detrital grains plus quartz overgrowths) comprised an average of 84.4% of the thin sections (Table 7). There is no significant difference between the composition of the Rock Creek and Upper Fernie sandstones as both plotted in the quartz arenite or sublitharenite fields on Folk´s QFL plot (Fig. 38). Pie diagrams showing the composition of all of the Jurassic sandstones are shown in Fig. 38B.

Monocrystalline quartz comprised the bulk of these sandstones (mean



(38) QFL triangle and pie diagrams showing framework composition, Fernie and Kootenay-Nikanassin sandstones.

75.4%) and individual grains were typically non-undulose and inclusion-free. Where original grain boundaries could be discerned, due to the presence of cloudy or inclusion-rich rims, the original grains are sub to well-rounded. Polycrystalline quartz comprises a small proportion of most Fernie sandstones (mean 5.1%) and each grain typically consists of 2-3 elongate crystals sutured together. Chert is the most common rock fragment in the Jurassic sandstones (average 3.5%) and consists of subequant, microcrystalline to cryptocrystalline quartz which is colorless to brownish-grey under plane light and dark grey to black under the binocular microscope. No feldspar was observed in any of the Fernie sandstones. Bright green glauconite grains were observed in most Rock Creek samples although, in most cases, these comprised a small proportion (mean 1.8%) of the sample. Opaque minerals, chiefly detrital magnetite, comprised a small proportion (mean 1.0%) of most of the Jurassic sandstones examined.

(ii) KOOTENAY-NIKANASSIN SANDSTONES

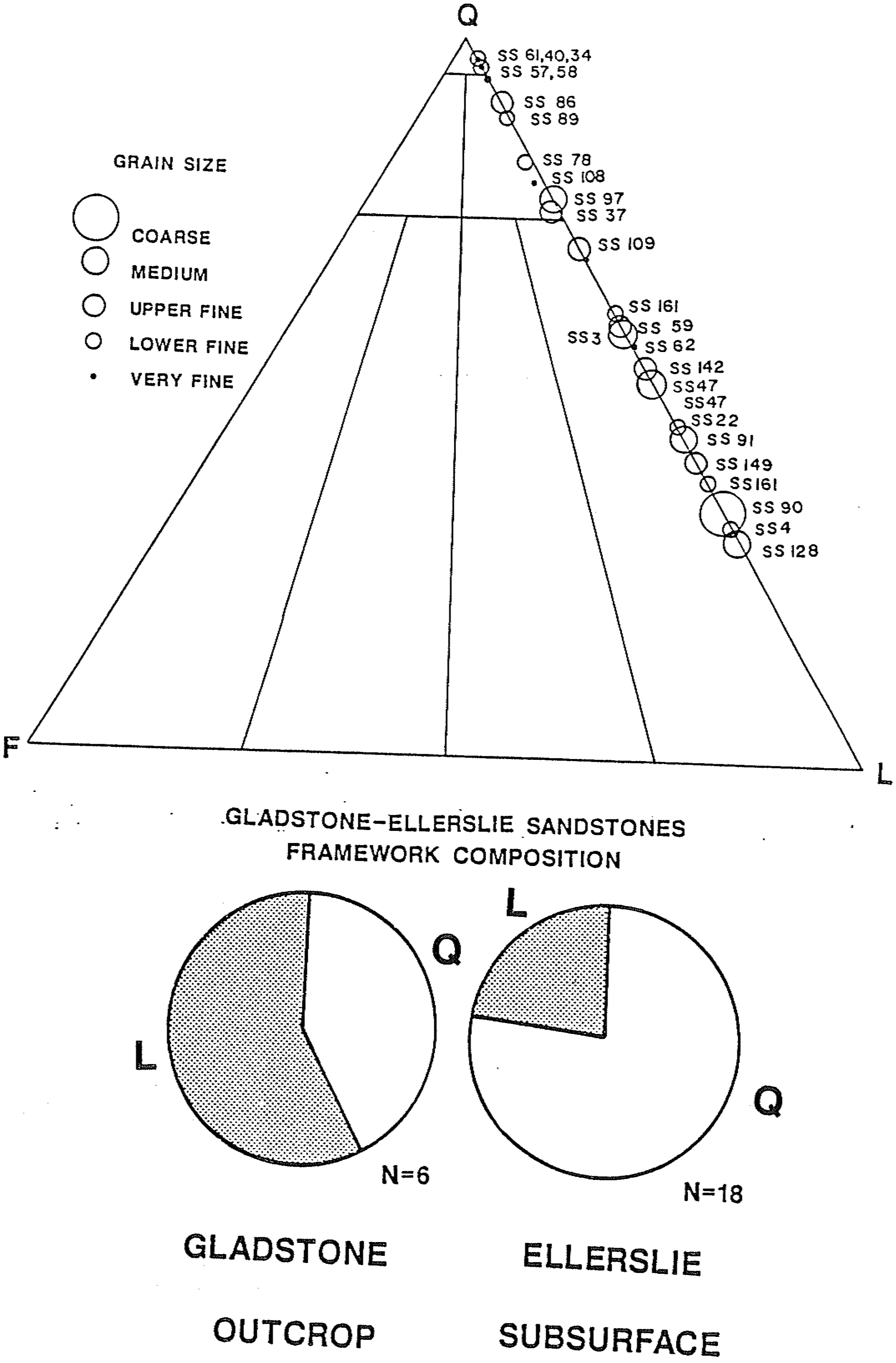
Seven samples of Kootenay-Nikanassin sandstones were point counted and this data is tabulated in Appendix 4A, summarized in Table 7, and plotted in Figs. 38A and B. All seven samples were comprised of variable proportions of chert and quartz and plotted in the litharenite field on Folk's (1980) QFL plot. All of the samples plotted along the Q-L axis as they contained no feldspar or igneous rock fragments. In general, the Nikanassin sandstones contained a higher proportion of quartz although it is not clear if this is a function of their generally finer grain size or a lateral change in provenance within the Late Jurassic interval.

The Kootenay-Nikanassin sandstones were dominated by monocrystalline quartz (mean 34.8%) and contained subequal amounts of chert (mean 29.3%) and minor proportions of polycrystalline quartz (mean 2.6%), carbonate rock fragments (mean 3.0%). The sandstones were typically tightly cemented with quartz overgrowths and some samples contained significant proportions of undifferentiated clay cement and/or matrix.

(iii) GLADSTONE-ELLERSLIE SANDSTONES

Six outcrop samples of sandstones from the Gladstone Formation and 18 core samples from equivalent Ellerslie sandstones were point counted and this data is compiled in Table 7 and plotted in Fig. 39. In general, these sandstones are coarser-grained, less well sorted, and contained much more chert than the underlying Jurassic sandstones (Fig. 39). On the QFL plot (Fig. 39A), the sandstones range in composition from quartz arenite, sublitharenite to litharenite and there is a crude relationship between quartz/lithic ratio and the grain size. In general, the very fine to fine-grained samples (plotted as small circles) are highly quartzose whereas the medium and coarse-grained sandstones (larger circles) are chert-rich and plot closer to the L-pole. Feldspar is completely absent in most samples and, where present, comprises less than 1% of the sample. These sandstones typically contain low proportion of clay cement-matrix (mean 10.7%) and are extensively cemented by quartz overgrowths and, in some instances, by carbonate cements.

Pie diagrams comparing the composition of Ellerslie and Gladstone sandstones are shown in Fig. 39B. Monocrystalline quartz comprised the bulk of the sandstones in both the Ellerslie interval (mean 54.2%) and the Gladstone (mean 31.0%). Polycrystalline quartz was more abundant in the Gladstone (mean 7.8%) as compared to the Ellerslie(mean 3.9%) whereas chert was much more abundant in the Gladstone-Gething (mean 28.5%) as compared to the Ellerslie (mean 16.3%). Most of the monocrystalline grains were non-undulose and most of the polycrystalline grains contained many more than three crystal-units per



(39) QFL triangle and pie diagrams showing framework composition, Early Cretaceous Gladstone-Ellerslie sandstones.

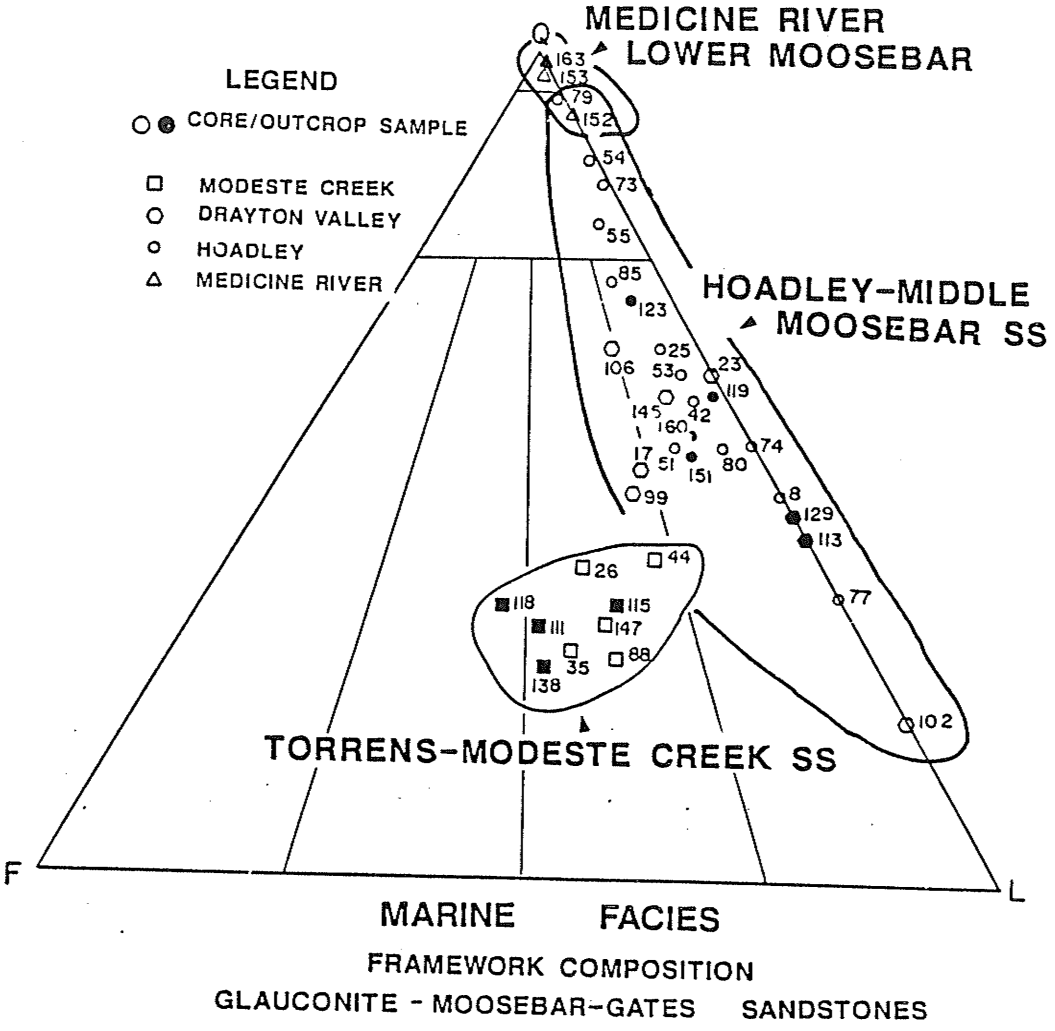
grain. Many polycrystalline quartz grains contain elongate, strained crystals with sutured boundaries and others contained a wide range in crystal sizes. The chert population consists of microcrystalline quartz which is highly argillaceous and commonly contains narrow fracture fillings of microcrystalline quartz. Detrital carbonate rock fragments are present in most outcrop samples (mean 6.0%) and consist of subrounded fragments of carbonate mudstone. The slides were not stained for carbonate so the mineralogy of the grains (i.e. dolomite or calcite) could not be determined. Unidentified rock fragments comprised an average of 11.5% of the Gladstone sandstones and 2.7 % of the Ellerslie sandstones. These grains are typically highly argillaceous, very finely foliated and probably represent shale or low grade (slate, phyllite) metamorphic rock fragments. No igneous rock fragments were recognized in any of these sandstones.

(iv) GLAUCONITE-MOOSEBAR SANDSTONES

Sandstones in the Glauconite and Moosebar and Gates Formations exhibit a wide range of framework composition as this interval records the transition from the quartz-chert assemblage at the base of the Blairmore-Mannville to the feldspar and volcanic-rich sandstones at the top of the interval. The three marine sandstones recognized in this interval each exhibit different framework compositions as do the various incised channel sandstones. The composition of the marine and channel sandstones will be discussed separately.

(a)MARINE SANDSTONES

Thirty-six samples of marine sandstones from the Glauconite-Moosebar-Gates interval were point counted and plotted on the QFL diagram (Fig. 40). The composition of these sandstones ranges from quartz arenite, sublitharenite,



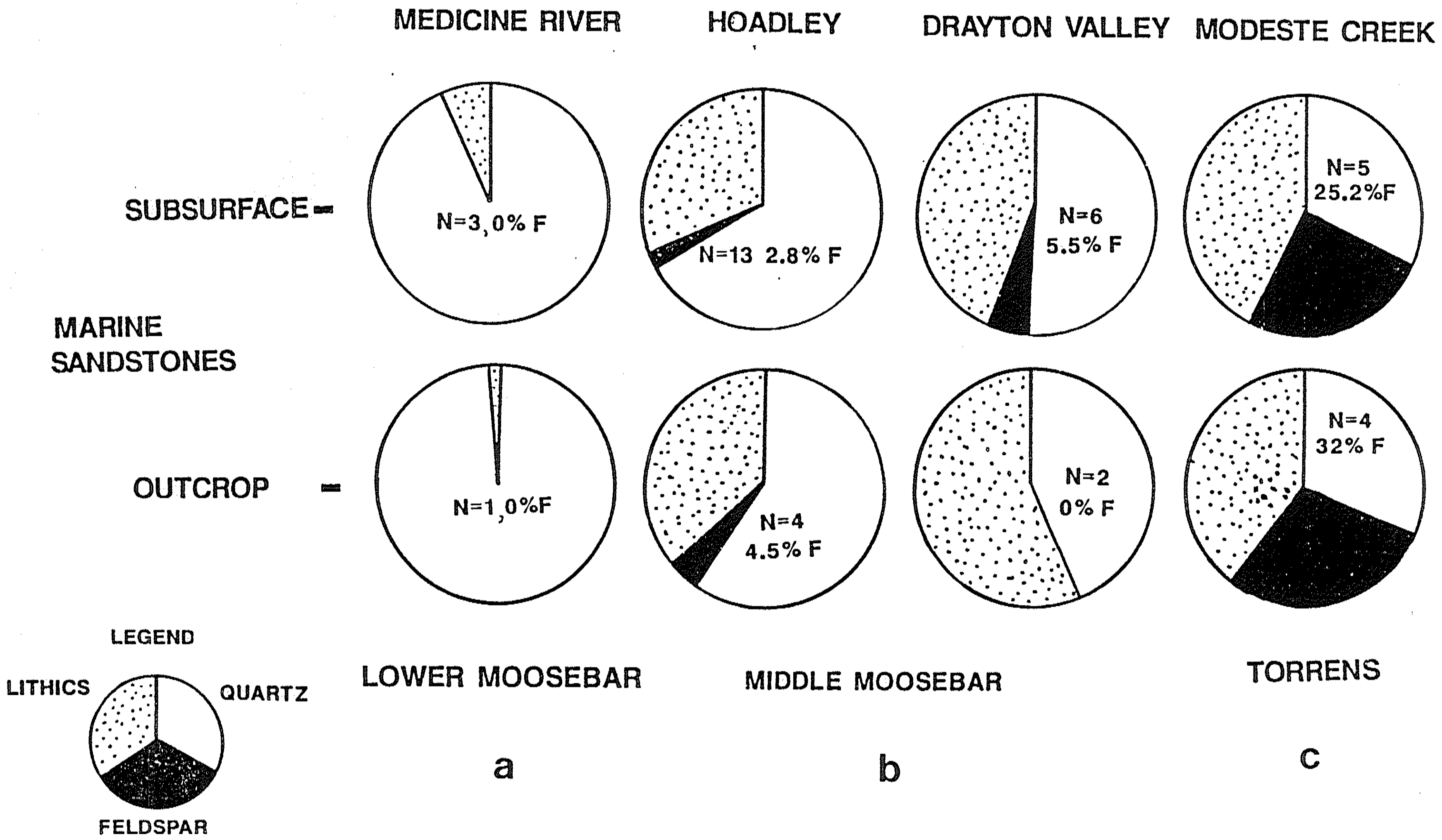
(40) QFL triangle showing framework composition of marine sandstones, Glauconite Formation.

litharenite, feldspathic litharenite to lithic arkose (Fig.40). However, there is strong stratigraphic control on framework composition within the interval as each of the three marine sandstone sequences exhibit different framework compositions (Fig. 41).

MEDICINE RIVER-LOWER MOOSEBAR SANDSTONES The subsurface samples of the Medicine River Member (SH-152, 153), and the equivalent Lower Moosebar sandstones in the Foothills (SH-163) are very fine to fine-grained, highly quartzose and plot in the quartz arenite to sublitharenite fields (Fig. 40). Both the core and outcrop samples are dominated by monocrystalline, non-undulose quartz (mean 84.5% and 98% respectively) and the sandstones are extensively cemented by syntaxial quartz overgrowths which obscure the outline of the original grains. No feldspar was observed in these sandstones although subequant grains of microcrystalline chert comprise a small proportion of the framework (3.5% and 1% respectively). Clay-carbonate matrix and/or cement is virtually absent in these sandstones (Table 7).

HOADLEY, DRAYTON VALLEY AND EQUIVALENT MIDDLE MOOSEBAR SANDSTONES

Twelve subsurface (core) samples of the marine sandstone comprising the Hoadley-Strachan Complex (Hoadley Member) and six outcrop samples of the equivalent middle Moosebar sandstones in the Foothills were analyzed. These data are tabulated in Appendix 4, summarized in Table 7 and plotted in Figs. 40 and 41. In general, these sandstones are fine to medium-grained, well sorted and plot in the sublitharenite to litharenite field (Fig. 40). These sandstones contain negligible clay cement and matrix (less than 5% in core and outcrop samples) and contain more chert and feldspar than the underlying Medicine River sandstones (Figs. 40, 41). Monocrystalline quartz dominates both the core and



(41) Comparison of marine sandstones in Glauconite Formation (and equivalent Moosebar-Gates sandstones), west-central Alberta.

outcrop samples (mean 47.9% and 40.5% respectively) whereas polycrystalline quartz comprises a smaller, but significant proportion (6.9% and 6.3% respectively) of all samples examined. Traces of unaltered and/or sericitized and carbonatized plagioclase are found in the Hoadley sandstone (mean 1.7%) and in the equivalent Upper Moosebar sandstones (combined mean 3.8%). The rock fragment population in the Hoadley and equivalent Upper Moosebar sandstones is dominated by chert (mean 15.3% and 20.0% respectively) and argillaceous, finely foliated grains (shale and low grade metamorphic fragments) which comprise an average of 8.5% and and 11.8% of the total modal count respectively.

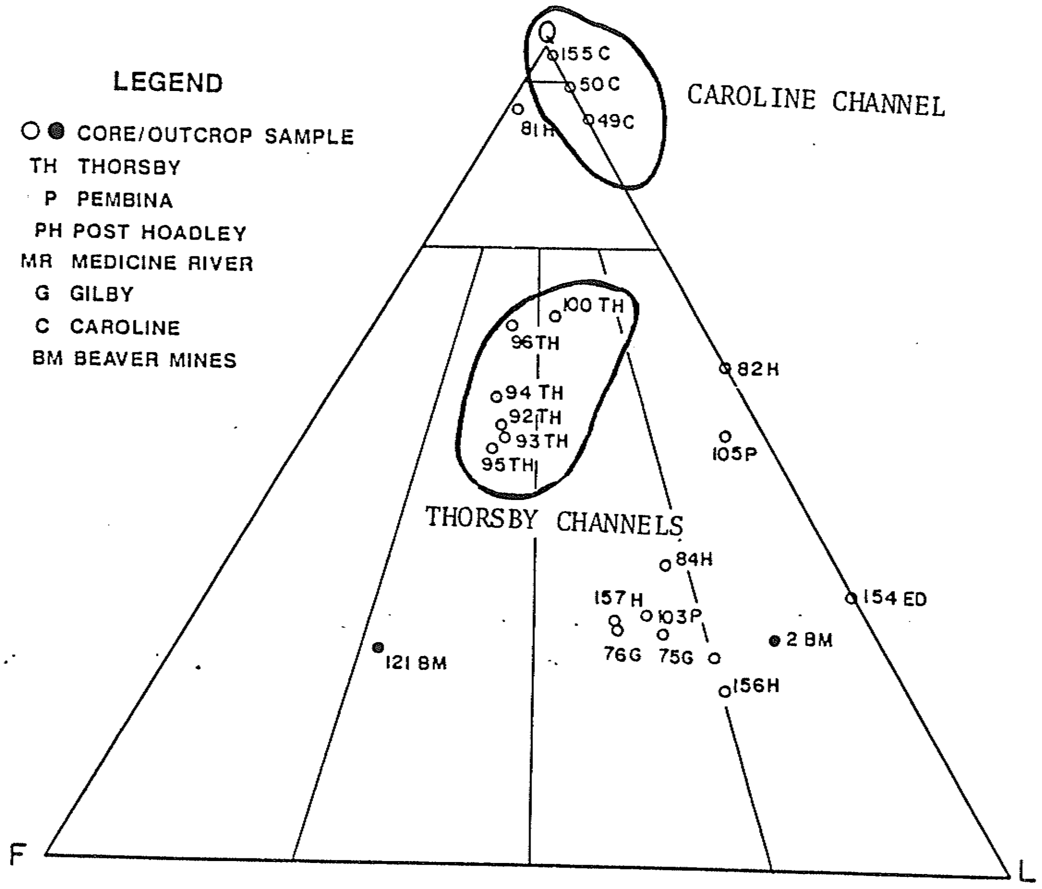
Six core samples of the shelf sandstones comprising the Drayton Valley Complex, and three samples of the equivalent middle Moosebar sandstones from the Crescent Falls and Ruby Creek sections, were analyzed. All of these samples plot as either litharenites or feldspathic litharenites (Fig. 40). The Drayton Valley sandstones contain more slightly more altered and unaltered feldspar (combined mean 5.7%) than the Hoadley Member sandstones (combined mean 1.8%) and considerably less monocrystalline quartz (mean 33.8%) than the Hoadley Member (mean 46.3%). Chert fragments and undifferentiated foliated argillaceous lithic grains were also more abundant in the Drayton Valley sandstones (Table 7).

MODESTE CREEK AND EQUIVALENT TORRENS SANDSTONES

The Modeste Creek-Torrens sandstones contain much more feldspar, less quartz and a much higher proportion of lithic fragments and clay-carbonate matrix and/or cement than the older sandstones in the Glauconite-Moosebar interval (Figs. 40, 41). These sandstones are typically fine-to medium-grained and plot in the feldspathic litharenite to lithic arkose field (Fig. 40). Monocrystalline quartz comprises a significant proportion of the Modeste Creek and Torrens sandstones (17.2% and 16% respectively) whereas polycrystalline quartz comprises a much smaller percentage (mean 5.2% and 7.0 %) respectively. Highly altered, sericitized yellow-stained feldspars, retaining relict albite or Carlsbad twinning, are common in the Torrens (mean 19%) and Modeste Creek sandstones (mean 15.6%). Chert comprises a significant proportion of both the Modeste Creek and Torrens sandstones (13.4% and 18.8% respectively). The undifferentiated rock fragments consist of brown, foliated, occasionally micaceous grains which probably represent shale and low grade metamorphic fragments. These sandstones are typically tightly cemented by a clay-carbonate matrix cement and it was virtually impossible to differentiate this material from squashed lithic grains. Framework material comprises only 68.8% of the Modeste Creek sandstones and 75.3% of the Torrens sandstones and the remainder of these slides consists of undifferentiated clay-carbonate matrix and cement plus squashed lithic grains.

(b) CHANNEL SANDSTONES

Twenty core samples of channel sandstones from the Glauconite Formation and two outcrop samples from Beaver Mines channel sandstones were point counted. These data are tabulated in Appendix 4 and plotted in Fig. 42. The framework composition of these sandstones ranges from quartz arenite to sublitharenite, subarkose, litharenite, feldspathic litharenite and lithic arkose. The composition of the incised channel sandstones is stratigraphically controlled, as the older channel sandstones (e.g. Caroline) are quartz-rich and the younger channel sandstones (e.g. Thorsby) contain abundant feldspar and volcanic rock fragments. The framework composition of the sandstones in each channel trend will be discussed in more detail in the following section.



CHANNEL FACIES

GLAUCONITE, GATES AND BEAVER MINES SANDSTONES
FRAMEWORK COMPOSITION

(42) QFL triangle showing framework composition of incised channel sandstones, Glauconite Formation.

CAROLINE CHANNEL

The northeast-trending Caroline channel which cuts through the Medicine River Member in the southern part of the study area is infilled with well sorted, highly quartzose sandstones which are petrographically very similar to the adjacent marine sandstones of the Medicine River Member (SH-49, 50 and 155, Fig. 42). Quartz comprises an average of 95% of the framework whereas lithic fragments (primarily chert) comprise the rest of the framework. No feldspar is present in these sandstones.

MEDICINE RIVER CHANNELS

The northwest-trending Medicine River-age channels, which incise down into the Medicine River and Hoadley-Strachan Complex are generally mud-filled. As a result, no sandstone samples were analyzed from these trends.

THORSBY-PEMBINA CHANNELS

The sandstones in the youngest channels in the study area contain a high proportion of feldspar and clay-carbonate cement and/or matrix and typically exhibit a dirty "greywacke" texture. These feldspathic channel sandstones comprise the reservoir in the Pembina and Thorsby fields and are also recognized along the Hoadley trend (SH-156, 157) and in the Gilby area (SH-75, 76, Fig. 42). The composition of the feldspathic channel sandstones is highly variable although the factors controlling this variability could not be determined with the limited number (16) of samples examined in this study. The Thorsby and Pembina channel sandstones contain low to moderate amounts of quartz (total quartz averages 36.4% of framework), abundant feldspar (combined altered and unaltered feldspar average 15.1%), and abundant chert (mean 17.1%) and volcanic rock fragments. These channel sandstones are petrographically similar to the feldspar-rich Modeste Creek sandstones which they incise down into.

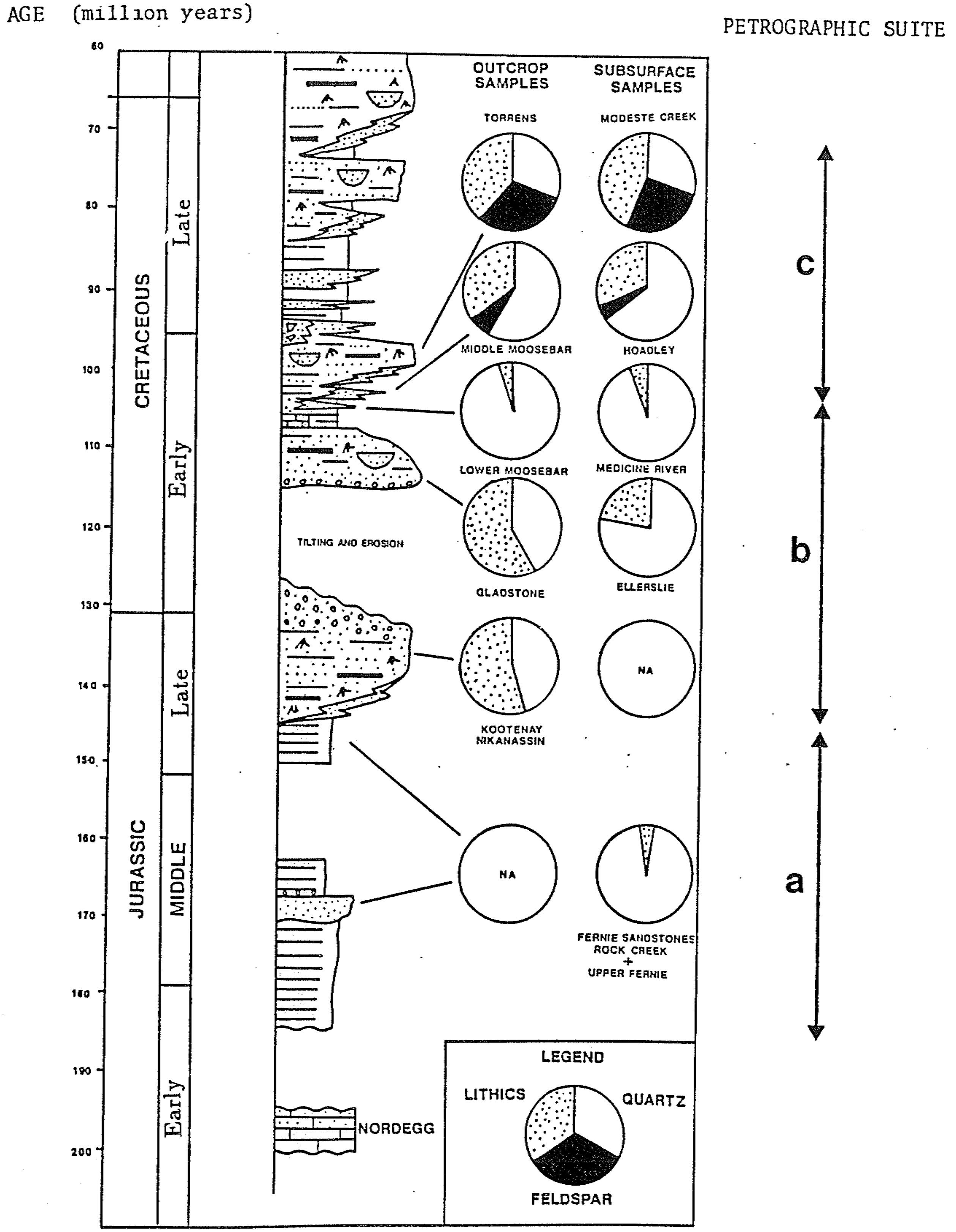
On the QFL plot (Fig. 42), the Thorsby sandstones plot in a separate field from the rest of these channel sandstones as they are more quartzose (combined mono- and polycrystalline quartz average 45.4%) and feldspar-rich (combined altered and unaltered feldspar 18.9%).

EDSON CHANNEL TREND

The single sample (SS-154) of sandstones from the Edson Channel trend (Fig. 11) is a medium-grained litharenite (Fig. 42). This sandstone is moderately quartzose (combined mono-and polycrystalline quartz 34.0%) but is dominated by lithic fragments (primarily chert) and is totally devoid of feldspar. This sample is petrographically similar to the older Gladstone-Ellerslie sandstones and very different from other (quartz and feldspar-rich) sandstones in the Glauconite Formation. Although the exact stratigraphic position of the Edson Channel is not well established (see Chapter 6), the lack of feldspar in the sandstones and the northeast trend of the complex suggests that it is age-equivalent to the Caroline Channel of the Medicine River area.

(D) SUMMARY OF STRATIGRAPHIC VARIATIONS IN FRAMEWORK COMPOSITION

In summary, there exists a very strong stratigraphic control on the framework composition of Jurassic-Early Cretaceous sandstones in western Alberta. This stratigraphic variation is best illustrated by plotting the average composition of core and outcrop samples of each major stratigraphic unit on a series of pie diagrams beside a stratigraphic column (Fig. 43). Three distinct framework suites can be recognized and include:



(43) Stratigraphic section of the Alberta Basin showing the framework composition of Jurassic-Early Cretaceous sandstones examined in this study. Chronostratigraphic time scale, and eustatic sea level and coastal onlap curves from Haq et.al. (1987) and information on the age of stratigraphic units from Poulton (1984); Stott (1984); and Rudkin (1964).

(a) the highly quartzose, fine-grained Middle to Late Jurassic sandstones of the Fernie Formation which contain virtually no feldspar and only traces of lithic (largely chert) fragments.

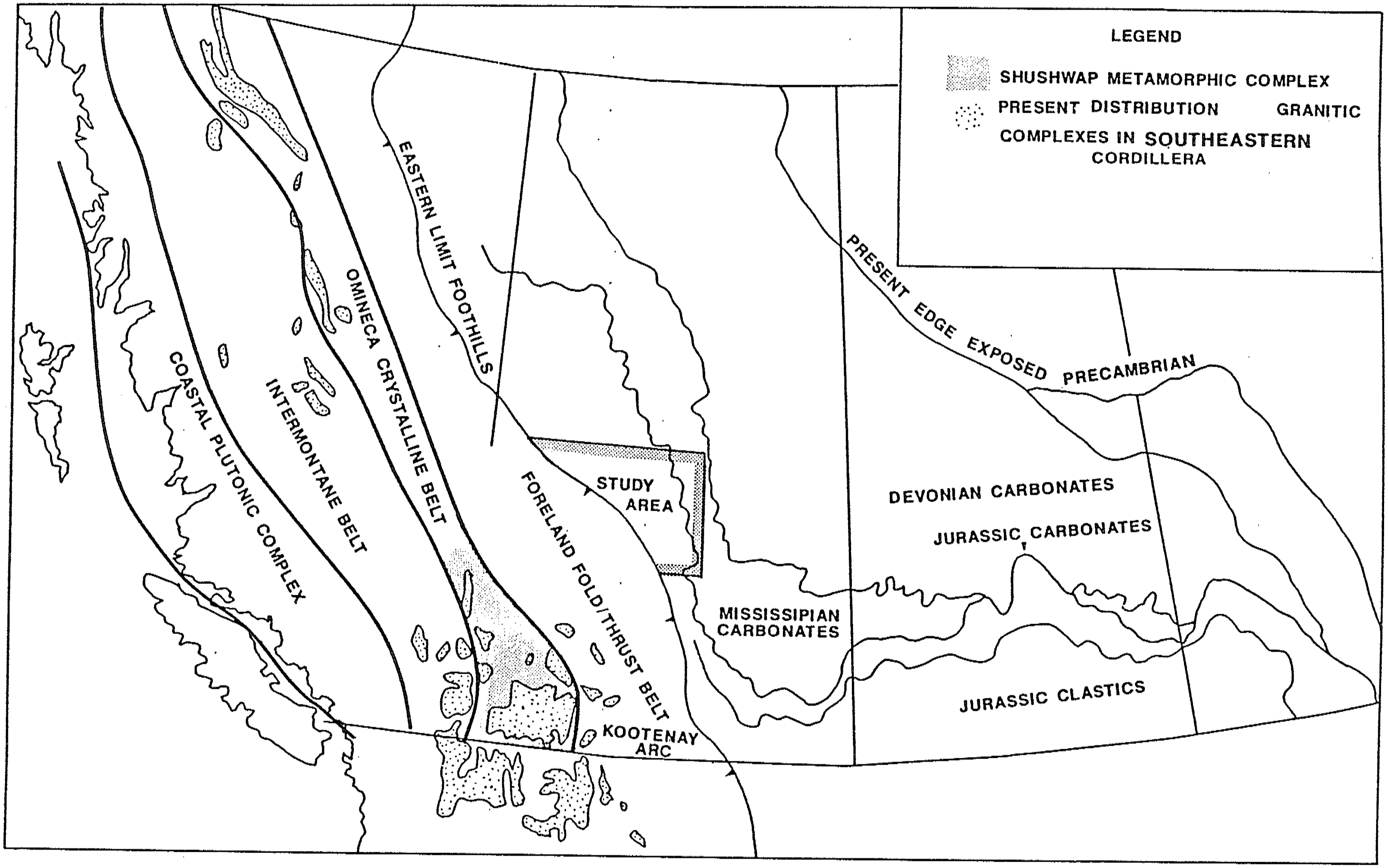
(b) the chert+quartz-rich, Late Jurassic Kootenay-Nikanassin interval, and the overlying Early Cretaceous Cadomin-Gladstone-Ellerslie interval. These sandstones contain no feldspar and little or no igneous and high grade metamorphic rock fragments. There is no pronounced compositional difference between the Kootenay-Nikanassin and Cadomin-Gladstone sandstones.

(c) the feldspar+lithic-rich Beaver Mines, Gates and Upper Mannville sandstones. The Glauconite-Moosebar interval appears to record the change in provenance during the Early Cretaceous as the basal Medicine River-Lower Moosebar sandstones contain no feldspar or volcanic fragments, the middle interval (Hoadley-Drayton Valley-Middle Moosebar sandstones) contains only a few percent feldspar and volcanic rock fragments, and the uppermost Modeste Creek-Torrens sandstones contain subequal proportions of quartz, rock fragments and chert.

(E) PROVENANCE OF JURASSIC - EARLY CRETACEOUS SANDSTONES

(i) MESOZOIC PALEOGEOGRAPHY OF THE ALBERTA BASIN

In order to relate the composition of Jurassic-Early Cretaceous sandstones in Alberta to potential source terranes a paleogeographic map showing the basin configuration at the time of deposition was constructed (Fig. 44). The eastern margin of the Alberta Basin was reconstructed by plotting the erosional edges, and lithologies, of major stratigraphic units subcropping below the pre-Cretaceous unconformity (Fig. 44). Sands derived from an eastern (cratonic) source should be dominated by quartz (either weathered from Precambrian crystalline rocks or recycled from older Jurassic sandstones) and chert



(44) Paleogeographic reconstruction, Western Canadian Sedimentary Basin showing subcrop edges on the pre-Cretaceous unconformity (redrawn from Rudkin 1964) and major tectonic elements in southern Cordillera (after Monger et al. 1982 and Archibald et al. 1983).

(reworked from the broad belt of Paleozoic carbonates which subcropped below the Mannville throughout most of the western Plains). The presence of numerous thick coals in the Jurassic and Early Cretaceous succession in the study area suggests that humid climates prevailed during their deposition. Under these conditions, it is unlikely that significant amounts of feldspar would have survived the 1000km (minimum) of transport between central Alberta and the closest exposures of crystalline Precambrian rock.

Reconstructing the paleogeography of the western margin of the basin is much more problematical as the spatial distribution of the allochthonous terranes in the Cordillera during the Early Cretaceous is poorly constrained. If no palinspastic corrections are attempted, three potential source areas which could have contributed sediment to the basin include:

a) the foreland fold/thrust belt, consisting largely of non to weakly metamorphosed Proterozoic-Paleozoic sediments (Spang et al. 1981).

b) the Shuswap Metamorphic Complex, consisting of amphibolite-facies metamorphosed sediments, and associated granitic intrusions of the Kootenay Arc (Archibald et al. 1983);

c) the Intermontane Belt (Quesnellia-Stikinia-Cache Creek terranes) consisting primarily of Late Paleozoic-Triassic volcanics and deep water sediments (Monger et al. 1982).

The major problem with reconstructing the Mesozoic paleogeography of the Cordillera is that there exists a wide range of estimates of displacement across the major strike-slip faults in the area. The tectonic model proposed by Price and Carmichael (1986) advocates that as much as 450 km of post-Early Cretaceous, north-south displacement has occurred along the Rocky Mountain-Tintina Trench in the northern Cordillera. Although they suggest that much less displacement is noted across this feature in the southern Cordillera (i.e., south of 52 degrees latitude), the potential source terranes for the Blairmore-Mannville sandstones could have been displaced several hundred kilometers since the Lower Cretaceous. The tectonic model proposed by Lambert and Chamberlin (1988) invokes much more relative displacement (1500-2000km) between the allochthonous terranes and the craton but they suggest that most of this was taken up by oblique subduction during the Jurassic. Using this tectonic scenario, there is little evidence that extensive, strike-slip displacement has occurred in the southern Cordillera since the Early Cretaceous. Since there is no agreement on the amount of displacement along these fault systems, no attempt was made to palinspastically restore the potential source terranes to their position during the Early Cretaceous.

(ii) METHODOLOGY

To evaluate the provenance of Jurassic- Cretaceous sandstones in the study area, a select number of representative samples were examined in detail. Several different petrographic techniques were employed and these data and interpretations are outlined in the following section.

The bulk framework composition of the Early Cretaceous sandstones was plotted on a series of diagrams proposed by Dickinson and Suczeck (1979) which relate framework composition to tectonic setting. In addition, the quartz, feldspar and lithic fragment population of several samples was analyzed separately for any provenance data which could be extracted. The quartz grains were described in terms of crystallinity and undulosity and these data were plotted on diagrams proposed by Basu et al. (1975) which relate these characteristics to tectonic setting. The composition and twinning habits of the feldspar fraction in several samples were compared with those described in various igneous and metamorphic rocks by Pittman (1970). As a final test of provenance, the major element chemical composition of the Early Cretaceous sandstones was plotted on a series of ternary diagrams proposed by Bhatia (1983) and Roser and Korsch (1986).

(a) BULK FRAMEWORK COMPOSITION

Dickinson and Suczek (1979) demonstrated that the tectonic setting of a sedimentary basin could be deduced from analysis of the framework composition of sandstones. To evaluate the provenance of the Early Cretaceous sandstones in central Alberta, the framework composition of fourteen samples of Early Cretaceous sandstones was recalculated in terms of their framework parameters (Table 8) and plotted on their QFL and QmFLt triangles (Fig. 45). On these plots, the framework population was recalculated to 100% and subdivided as follows;

1) Q-stable quartzose including Qm (monocrystalline) plus Qp (polycrystalline quartz and chert grains).

2) F-feldspar including P (plagioclase) and K (K-feldspar).

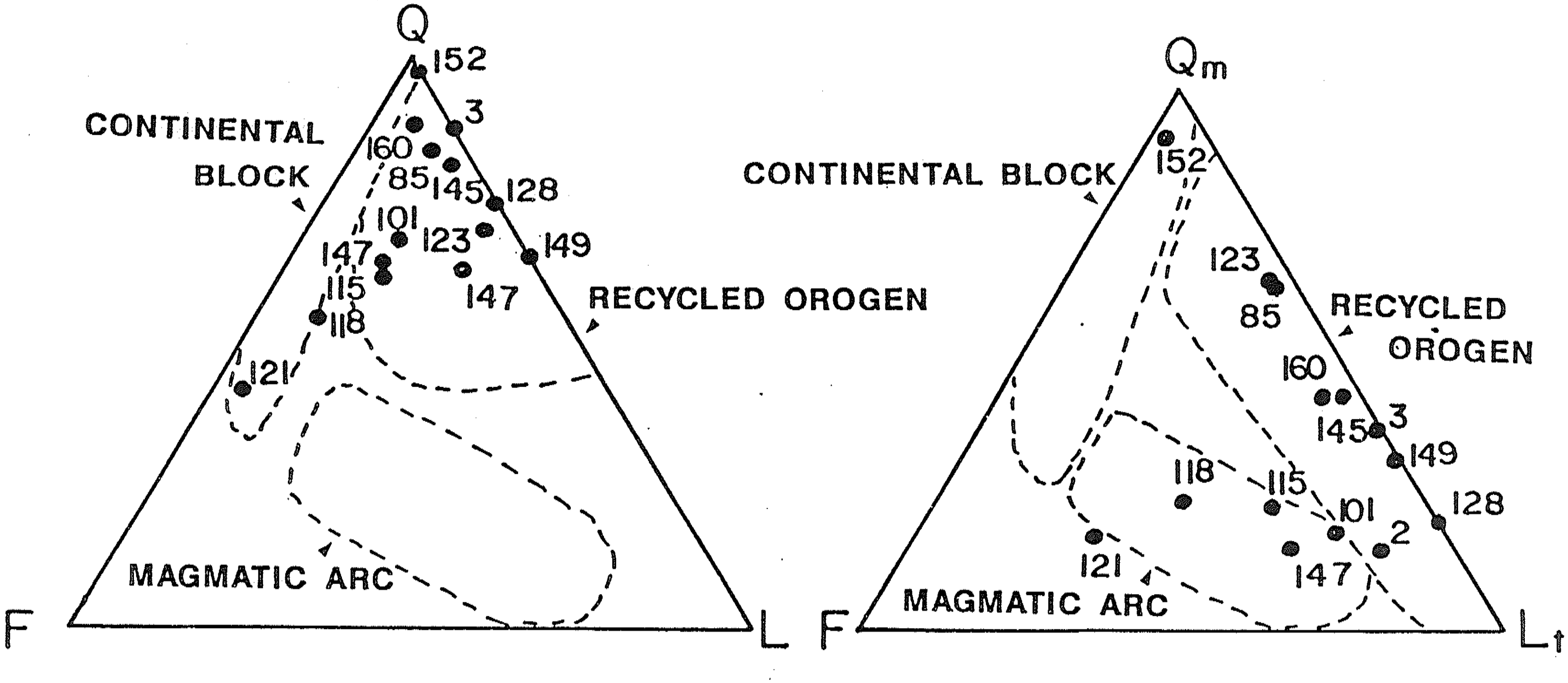
3) L-unstable lithics including Lv (volcanics plus metavolcanics) and Ls (sedimentary and metasedimentary)

4)Lt-total lithics including Ls plus Lv plus Qp.

Although Dickinson and Suczek (1979) specifically excluded heavy minerals and calcareous grains from their modal counts, more recent studies (e.g., Mack 1984) have demonstrated that detrital carbonates do carry a signature of source terrain and should be included in the Ls population. The detrital carbonate grains in the sandstone in this study were included as lithic sedimentary (Ls) grains in the framework recalculation although it is emphasized that their low abundance in all samples would not significantly alter their position of the diagram.

	Sample # GRAIN SIZE	Stratigraphic Unit	Folk			Dickenson & Suczek 1			Dickenson & Suczek 2		
			Q	F	L	Q	F	L	Qm	F	Lt
outcrop samples	SS 118 FG	Torrens	33	36	31	55	36	9	28	36	36
	SS 115 FG	Torrens	33	24	43	62	24	14	24	24	52
	SS 160 LFG	Upper Moosebar	54	6	40	79	6	15	45	6	49
	SS 123 UFG	Upper Moosebar	71	4	25	90	5	5	66	5	29
	SS 121 UFG-FG	Beaver Mines	26	53	21	43	53	4	20	53	27
	SS - 2 UFG-MG	Beaver Mines	28	11	61	59	11	30	17	11	72
	SS - 3 LMG-LCG	Gladstone	50	0	50	90	0	10	40	0	60
	SS 128 UFG-LMG	Gladstone	31	0	69	76	0	24	21	0	79
	SS 149 VFG-FG	Gladstone	42	0	58	66	0	34	34	0	66
core samples	SS 147	Modeste Creek	31	26	43	64	26	10	19	26	55
	SS 145 UFG	Drayton Valley	59	6	35	81	6	13	46	6	48
	SS 85 UFG	Hoadley	73	5	22	85	5	10	65	5	30
	SS 152 VFG	Medicine River	93	0	7	99	0	1	91	0	9
	SS 101 UFG-LMG	Pembina Channel (G)	26	18	56	67	18	15	20	18	62

Table 8 Petrographic (framework) composition of Blairmore-Mannville sandstones selected for provenance evaluation showing the framework parameters employed by Folk (1980) and Dickinson and Suczek (1979).



SANDSTONE FRAMEWORK PROVENANCE PLOTS

(45) Framework composition of medium-grained Blairmore-Mannville sandstones from central Alberta, plotted on provenance triangles proposed by Dickinson and Suczek (1979).

GLADSTONE SANDSTONES

All three samples of the Gladstone Formation (#3,128, and 149) plot along the Q-L axis in the recycled orogen field on both the QFL and QmFLt diagrams. According to Dickinson and Suczek (1979) this (recycled orogen) field is comprised of three distinct sub-fields which include:

1) a subduction zone complex source which generates chert-serpentine-mafic volcanic-rich sandstones,

2) a foreland fold/thrust belt source which recycles quartz and chert-rich detritus from from older sedimentary sequences, and

3) a collision orogen source from which quartz, chert and lithic-rich sandstones are produced from erosion of metasedimentary rocks exposed in nappes and thrust sheets which flank the suture zone.

While the subduction zone complex can be eliminated as a potential source area, due to the absence of diagnostic serpentine, the distinction between foreland fold/thrust belt and collision orogen provenances on the QFL plot is more difficult. Mack (1981) was able to discriminate between recent detritus eroded from a sedimentary (foreland fold/thrust) terrain from sand eroded from a low-grade metamorphic rocks in a collision orogen by comparing the composition of the lithic fragments. He noted that the sedimentary rocks contributed quartz and chert-rich sands which contained a significant proportion (average 27%) of pelitic rock fragments. Low grade metamorphic terrains contributed subequal amounts of mono- and polycrystalline quartz and foliated quartz-mica aggregates (Mack 1981). Sandstones derived from higher grade metamorphics in a collision orogen (e.g. Tertiary sandstones from the Bay of Bengal) are also quartz-rich but contain an average of 30% feldspar (dominantly plagioclase) and an average of 15% lithic fragments which were dominated by quartz-mica aggregates (Mack 1981).

The bulk framework composition of the quartz and chert-rich, and quartz-mica and feldspar-deficient Gladstone samples (#3, 128, and 149) indicate that these sandstones were probably derived from a non to weakly metamorphosed foreland fold/thrust belt which flanked the ancestral Cordillera. There is no evidence of middle to high-rank metamorphic or plutonic rocks contributing sediment to the basin during this time.

BEAVER MINES-TORRENS-MODESTE CREEK SANDSTONES

The feldspar and volcanic-rich Beaver Mines and Torrens-Modeste Creek sandstones (# 101, 115, 118, 121 and 147) are more difficult to interpret as they straddle the continental block-recycled orogen fields on the QFL plot and fall within the magmatic arc field on the QmFLt triangle (Fig. 45). The absence of K-feldspar is inconsistent with a continental block provenance or a high grade metamorphic source (Dickinson and Suczek 1979). Moreover, the paucity of foliated quartz-mica aggregates (Table 11) and abundance of volcanic rock fragments in these sandstones is inconsistent with a metasedimentary (collison orogen) source (Mack 1981).

The feldspathic, volcanic-rich sandstones (Beaver Mines -Gates Formations were probably derived from a composite source terrane which included a weak to non-metamorphosed foreland fold/thrust belt, as well as volcanic highlands. The fresh, unaltered nature of the feldspars and rock fragments have been cited as evidence for coeval (Early Cretaceous) volcanism in the Cordillera (Glaister 1959; Mellon 1967; Putnam and Pedskalny 1983) although large volumes of volcanic rocks of this age are not presently preserved in the southern Cordillera (Souther 1977). A detailed discussion of possible source terranes will be presented at the end of this chapter.

GLAUCONITE-MOOSEBAR SANDSTONES

The Hoadley and Drayton Valley sandstones in the Plains (# 85, 145), and equivalent middle Moosebar sandstones (#123 and 160) in the Foothills exhibit a framework composition on the QFL and QmFLt plots which is intermediate between that of the underlying quartz and chert-rich Gladstone and the overlying feldspathic, volcanic-rich Beaver Mines-Torrens-Modeste Creek sandstones (Fig. 45). These sandstones thus record the transition from a sedimentary provenance to a volcanic plus sedimentary provenance. This change in provenance was apparently abrupt as the transition generally occurs over a few metres of stratigraphic section and there is little evidence of a major depositional hiatus or unconformity separating the different compositional suites in the study area. In this sense, the transition does not appear to represent a gradual unroofing of a collision orogen, as Rapson (1965) suggested, since this process probably generates gradual changes in composition over very large stratigraphic intervals (e.g.,Dorsey 1988). The provenance change in western Alberta appears to record the abrupt introduction of volcanic material into a foreland basin which had previously received only recycled sedimentary detritus eroded from a non to weakly-metamorphosed fold/thrust belt.

(b) QUARTZ POPULATION

The petrographic characteristics of detrital quartz were first related to the type and character of rock exposed in the source area by Sorby in 1877 and have since been investigated by many petrologists (see Blatt and Christie (1963) for a review). Early workers considered that monocrystalline non-undulose quartz was diagnostic of a plutonic provenance whereas polycrystalline and highly undulose quartz was characteristically derived from metamorphic terranes. These generalizations were challenged by Blatt and Christie (1963) who documented that highly strained, undulose grains could be derived from both plutonic and metamorphic terranes and concluded that only crude interpretations of provenance could be made on the basis of quartz characteristics. This controversey was resurrected by Basu et al. (1975) who demonstrated that the source terrane of modern and ancient (medium-grained) sands of differing provenance could be discriminated if the crystallinity and the degree of undulosity of the quartz was considered. They divided the quartz population into four groups which include:

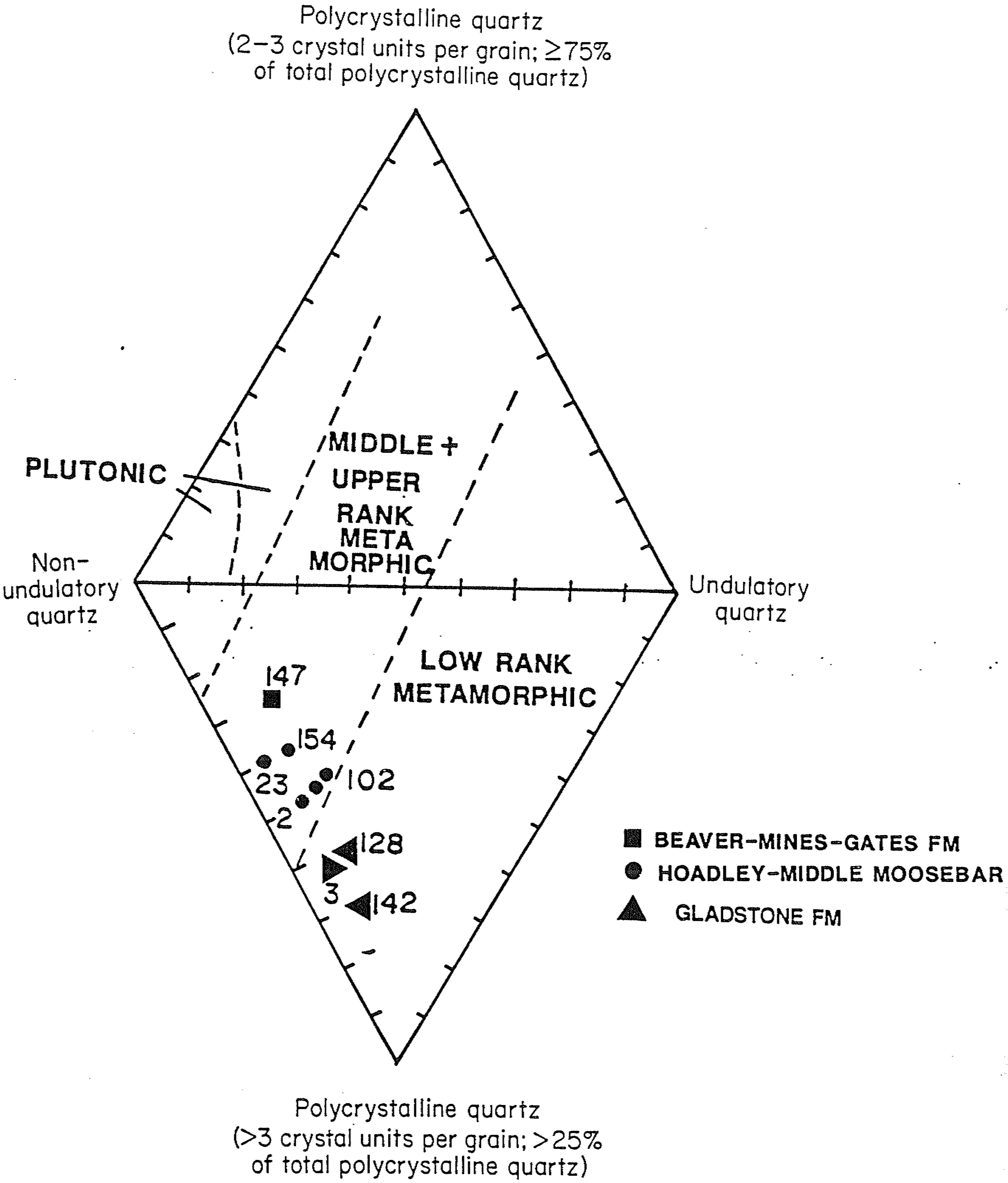
1) monocrystalline (less than 5 degrees undulosity)
2) monocrystalline (more than 5 degrees undulosity)
3) polycrystalline (2-3 crystals/grain)
4) polycrystalline (more than 3 crystals/grain)

They demonstrated that modern sands of differing provenance plotted in separate fields which reflected the degree of metamorphism, and the proportion of plutonic rocks exposed, in those source areas. Their data confirmed earlier observations that plutonic-derived quartz grains were coarser-grained, less undulose, and contained less polycrystalline grains than lower to upper grade metamorphic rocks.

Three thin sections of the Gladstone Formation (#3, 128, and 142), four samples of the Glauconite-Moosebar sandstones (#23, 102, 147 and 154), and one sample of the Beaver Mines Formation (#2) were counted and the data are tabulated in Table 9 and plotted in Fig. 46. The quartz populations of all of these samples plot in the lower triangle and span the lower to upper metamorphic fields (Fig. 46). There appears to be some stratigraphic control on the quartz population as the oldest (Gladstone) sandstones plot in the low rank metamorphic field whereas the younger Moosebar-Glauconite and Beaver Mines

SAMPLE NUMBER STRAT. UNIT	MONOCRYSTALLINE		POLYCRYSTALLINE	
	NON-UNDULOSE	UNDULOSE	2-3 CRYSTALS/GRAIN	>3 CRYSTALS/GRAIN
SS-2 Beaver Mines	45	9	24	22
SS-3 Gladstone	34	6	23	37
SS23 Drayton Valley	58	5	14	23
SS102 Drayton Valley (First Count)	44	14	17	25
SS102 (Second Count)	43	14	13	30
SS128 Gladstone	32	11	24	33
SS142 Gladstone	23	10	7	60
SS147 Modeste Creek	63	12	13	12
SS154 Edson Channel	54	11	6	29
Mean n=8 (delete second count #10)	44.1	9.8	16.0	30.1

TABLE (9) Petrographic characteristics (undulosity/ polycrystallinity) of quartz population



(46) Undulosity and polycrystallinity of quartz grains in Blairmore-Mannville sandstones, plotted on triangular plots proposed by Basu et al. (1975).

samples plot in the middle/upper rank metamorphic field.

The low-rank metamorphic source terrane interpreted for the Gladstone samples is consistent with the foreland fold/thrust belt provenance indicated by the bulk framework composition, described previously. However, the middle to upper rank metamorphic provenance suggested for the Glauconite-Moosebar and Beaver Mines sandstones is problematical. Although Late Mesozoic middle-high rank metamorphic rocks of are presently exposed in the southeastern Cordillera south and west of the study area, (i.e. Shuswap Metamorphic Complex and Kootenay Arc), it appears that these were not unroofed prior to the Eocene (Archibald et al. 1983). Moreover, very few K-feldspar grains (Table 10) or foliated quartz-mica lithic fragments (Table 11) were noted in the samples examined in this study (Table 11) or in previous studies (Rapson 1965; Mellon 1967). Significant proportions of both of these components would be generated by the erosion of a high-grade metamorphic or plutonic terrane (Mack 1981). It was noted that the data presented by Basu et al. (1975) did not include volcanically-derived sandstones, and it appears that these plots can not be used the to determine provenance of the Beaver Mines and Gates sandstones. The presence of volcanic quartz, which is monocrystalline, nonundulose and petrographically indistinguishable from plutonic quartz (Blatt et al. 1980, p.289), would skew the points to the plutonic apex, even if no plutonic rocks were exposed in the source area.

In summary, detailed analysis of the quartz population in the Gladstone samples suggests that they were derived from erosion of low rank metamorphic rocks and this is consistent with the interpretation made on the basis of bulk framework composition. The provenance of the feldspathic, volcanic-rich Upper Blairmore-Mannville sandstones could not be established with this method.

(c) FELDSPAR POPULATION

Previous studies (e.g., Pittman 1970) have noted that provenance information can be also be derived from detailed analysis of the feldspar fraction in sandstones. Four feldspar-rich sandstones were selected from the upper (feldspathic) part of the stratigraphic interval studied (Beaver Mines and Thorsby channels, and the Modeste Creek Member) and the twinning and zoning characteristics of one hundred feldspar grains in each sample was tabulated (Table 10).

In all four samples, the entire feldspar population was comprised of plagioclase. Most of the grains were untwinned (average 65.5%) and most (97%) of the grains showed no evidence of zoning. Albite twinning was most common (average 29.8% of grains) and Carlsbad and combined albite-Carlsbad twinning was much less common (average 2.8 and 0.5% respectively). In most grains, the high degree of alteration hindered determination of the style of zoning (i.e. progressive versus oscillatory) in the grains although progressive zoning (Pittman 1970) was recognizable in a few grains. Although most grains are partially to completely altered to sericite and carbonate (see chapter on diagenesis), the composition of six unzoned feldspar grains was determined using a combined Carlsbad-Albite twinning method (L. D. Ayres, pers. comm., 1977) ranged from An_{8-26}(average An_{18}).

The feldspar population of sandstones is more difficult to interpret than the other framework components as this fraction is particularly susceptible to diagenetic alteration. If the detrital plagioclase has not been altered, then its composition can be linked to the type of igneous rocks and the grade of metamorphic rocks from which it is derived (Pittman 1970). On this basis, the albite-rich plagioclase in the Early Cretaceous sandstones examined in this study could have been derived from either felsic intrusive and/or extrusive

Sample # Stratigraphic Unit	Twinning				Zoning	
	Albite	Carlsbad	Combined Alb-Carls.	Un-Twinned	Strongly Zoned	Unzoned
SS-2 Beaver Mines	23	6	1	70	5	95
SS-121 Beaver Mines	28	2	2	68	0	100
SS-101 Glauconite FM, Thorsby	37	2	1	60	3	97
SS-147 Modeste Creek	33	3	-	64	4	96
Average	30.3%	3.2%	1.0%	65.5%	3.0%	97.0%

Table 10 Petrographic characteristics of the feldspar population, Blairmore-Mannville sandstones

rocks, low-grade (greenschist-lower amphibolite facies) metamorphic rocks, or spilitized basalts (Hyndman 1985, p. 183, 252, 297 and 458). However, previous researchers (e.g., Ghent and Miller 1974; Mellon 1967; Putnam and Pedskalny 1983) documented extensive albitization of the plagioclase grains in Early Cretaceous sandstones equivalent to those studied in this thesis. The uniform, albitic composition of the feldspar grains examined in this thesis suggests that these grains have been diagenetically altered. For this reason, the composition of the feldspars can not be used to interpret provenance of the detritus.

Pittman (1970) noted that twinning characteristics of plagioclase was also indicative of provenance as metamorphic plagioclase was largely untwinned whereas volcanic and plutonic plagioclase crystals commonly exhibit both albite and simple (Carlsbad) twinning. Zoning, particularly the oscillatory variety, is indicative of volcanic or hypabyssal intrusive source rocks. Based on these observations, the predominance of non-twinned plagioclase and virtual absence of zoning (Table 10) in the Early Cretaceous sandstones examined in this report is indicative of a low grade metamorphic source. This interpretation is difficult to reconcile with the observation that that foliated quartz-mica (metamorphic) grains are rare in the Early Cretaceous sandstones whereas volcanic fragments are very commonly associated with these feldspathic sandstones (Rapson 1965; Mellon 1967; Table 11 of this study). The reason for the discrepancy in provenance interpretation is unclear but it is possible that any relict zoning textures in volcanically-derived detrital plagioclase may have been destroyed during subsequent diagenetic alteration.

Sample Number Stratigraphic Unit	Volcanic	Chert	Detrital Carbonate	Siltstone	Microcrystalline		Micaceous/Foliated (Schist/Phyllite)
					Foliated (Shale, Slate)	Non-Foliated	
SS-2 Beaver Mines	3	42	2	5	15	30	3
SS-121 Beaver Mines	11	35	2	1	12	37	2
SS 147 Modeste Creek	5	46	1	3	16	26	3
SS 101 Glauconite Channel (Pembina Trend)	9	50	13	7	8	11	2
SS 128 Gladstone	-	75	4	7	3	11	-
SS 149 Gladstone	-	88	-	6	-	6	-

Table 11 Petrographic characteristics of the rock fragment population of medium-grained sandstones from Blairmore, Luscar and Mannville interval.

(d) MAJOR ELEMENT CHEMISTRY; STRATIGRAPHIC VARIATIONS AND PROVENANCE IMPLICATIONS

Fifteen samples of Early Cretaceous sandstones were analyzed for major element composition by the x-ray fluorescence laboratory at the Geological Survey of Canada in Calgary. This data, expressed in terms of weight percent oxides, is summarized in Table 12 and plotted as points on a series of histograms (Fig. 47). These graphs were constructed by grouping the data on the basis of stratigraphy and plotting the weight percent oxide in each sample on the histograms. The three groups identified include:

1) lower suite, consisting of Gladstone channel sandstones.

2) middle suite, consisting of the Medicine River-Hoadley-Drayton Valley and equivalent Moosebar marine sandstones.

3) upper suite, consisting of Modeste Creek-Torrens marine sandstones, plus the feldspathic sandstones from the Beaver Mines Formation, and the Thorsby and Pembina channel systems.

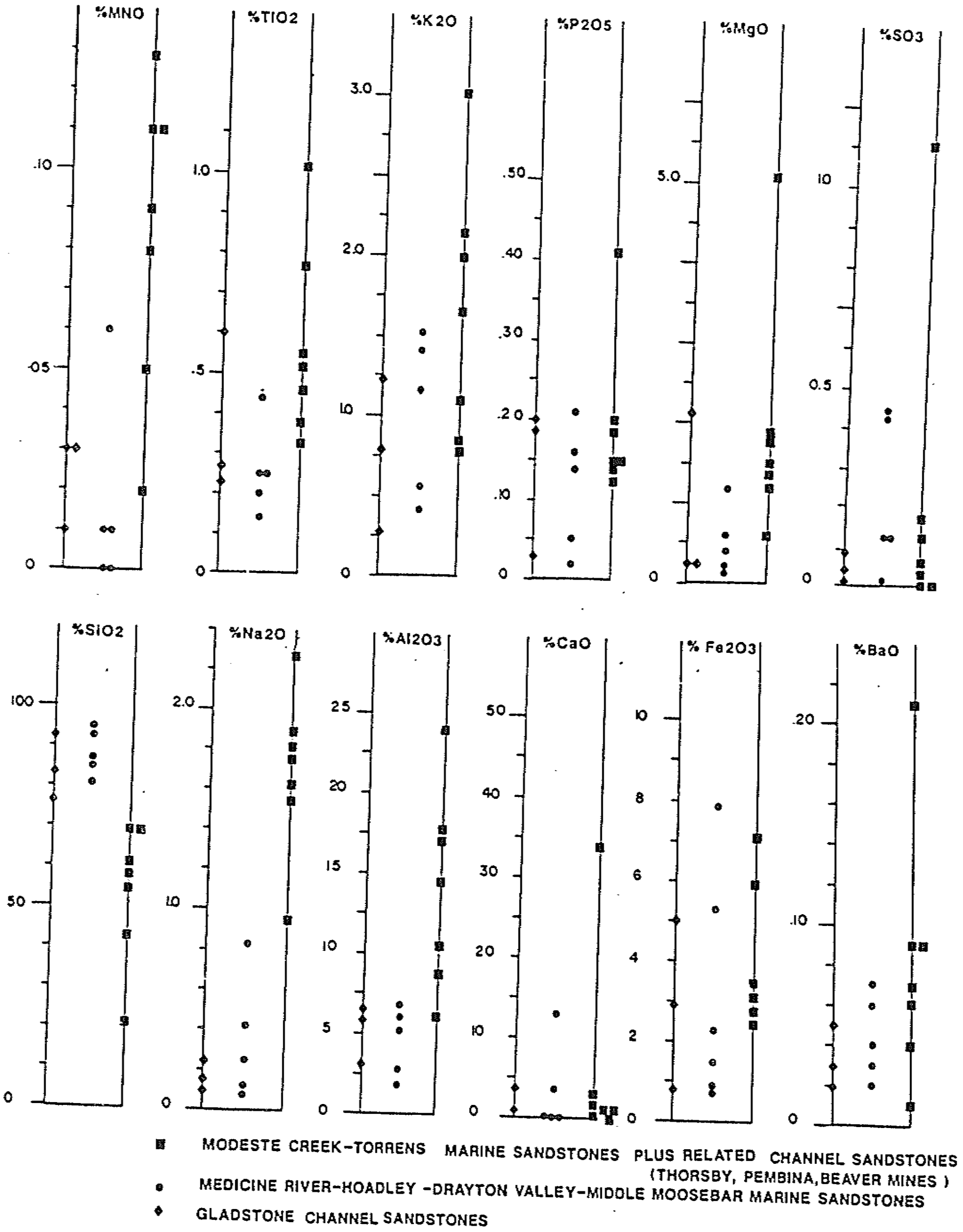
On these graphs (Fig. 47), the weight percent oxide values from the oldest (lower) suite) are plotted on the left vertical line, the middle suite is plotted in the center of the diagram and the youngest (upper) suite is plotted on the right vertical line. Systematic stratigraphic variations in chemical composition are evident and these are best demonstrated by comparing the range of values for sandstones which comprise each suite. Three generalizations can be made concerning chemical composition.

1) The lower sandstone suite is characterized by very high SiO_2 values and low Na_2O, Al_2O_3, Fe_2O_3, MnO, TiO_2, K_2O, MgO, and SO_3 values, compared to the middle and upper suites (Fig. 47). This is consistent with the petrographic observations that these sandstones are dominated by quartz and chert and

	Sample No.	Fe_2O_3	MnO	TiO_2	BaO	CaO	K_2O	P_2O_5	Al_2O_3	SiO_2	MgO	Na_2O	SO_3
UPPER SUITE MODESTE CREEK-TORRENS MARINE SANDSTONES PLUS RELATED CHANNEL SANDSTONES (PEMBINA THORSBY-BEAVER MINES)	SS115 (T)	2.54	0.02	0.52	0.09	0.69	2.00	0.13	17.21	69.22	0.64	2.24	0.0
	SS118 (T)	2.79	0.11	0.33	0.01	34.17	0.86	0.14	6.18	21.30	1.41	0.95	0.01
	SS147 (MC)	7.96	0.13	0.55	0.06	1.04	2.16	0.19	14.42	61.07	1.50	1.82	0.12
	SS93 (TH)	3.18	0.05	0.46	0.09	3.69	1.14	0.15	10.49	69.16	1.89	1.64	0.17
	SS101 (P)	7.15	0.09	0.39	0.04	13.14	0.81	0.15	8.76	42.50	5.15	1.54	1.10
	SS2 (BM)	3.52	0.08	1.02	0.21	1.85	3.03	0.41	23.85	54.96	1.23	1.79	0.06
	SS121 (BM)	5.96	0.11	0.77	0.07	2.74	1.65	0.20	17.63	59.75	1.79	1.90	0.03
MIDDLE SUITE MEDICINE RIVER-HOADLEY-DRAYTON VALLEY-MIDDLE MOOSEBAR MARINE SANDSTONES	SS152 (MR)	0.79	0.00	0.44	0.03	0.04	0.41	0.05	1.72	94.77	0.12	0.11	0.02
	SS85 (H)	1.54	0.00	0.20	0.06	0.04	1.42	0.02	5.35	87.08	0.43	0.25	0.43
	SS145 (DV)	2.36	0.01	0.25	0.07	0.30	1.52	0.21	6.06	85.07	0.60	0.43	0.44
	SS123 (MM)	0.94	0.01	0.14	0.02	0.29	0.56	0.66	2.81	92.87	0.20	0.09	0.01
	SS160 (MM)	5.33	0.06	0.25	0.04	0.73	1.13	0.14	6.82	80.57	1.20	0.83	0.12
LOWER SUITE GLADSTONE CHANNEL SANDSTONES	SS-3 (G)	5.02	0.03	0.23	0.03	0.35	0.79	0.20	6.37	83.94	0.25	0.11	0.08
	SS128 (G)	2.92	0.03	0.27	0.05	3.71	1.24	0.19	6.38	76.27	2.12	0.14	0.03
	SS149 (G)	0.81	0.01	0.60	0.02	0.66	0.29	0.03	3.08	92.42	0.25	0.22	0.02

T - Torrens, MC - Modeste Creek, TH - Thorsby, P - Pembina, BM - Beaver Mines, MR - Medicine River, H - Hoadley, DV - Drayton Valley, MM - Middle Moosebar, G - Gladstone

(12) Major element composition of representative samples of marine and non-marine Blairmore-Mannville sandstones.



(47) Histogram plots showing major element chemical composition of Blairmore-Mannville sandstones.

contain virtually no ferromagnesium or aluminosilicate minerals or igneous or metamorphic rock fragments.

2) The upper suite contains substantially lower values of SiO_2 and much higher values of all other oxides, than the lower suite described above. This is consistent with petrographic observations that these sandstones contain abundant feldspar and volcanic rock fragments and a much higher proportion of clay-carbonate matrix. One sample in this suite (# 118) contains much higher values of CaO and lower values of SiO_2 and Al_2O_3 than all other samples (Table 12). These anomalous values reflect the pervasive carbonatization recognized in this slide.

3) Sandstones from the middle suite generally exhibit oxide values which are intermediate between those of the upper and lower suites. This is consistent with the interpretation that these sandstones comprise a transition suite between the older quartz and chert-rich sandstones and the younger, feldspathic, volcanic-rich sandstones.

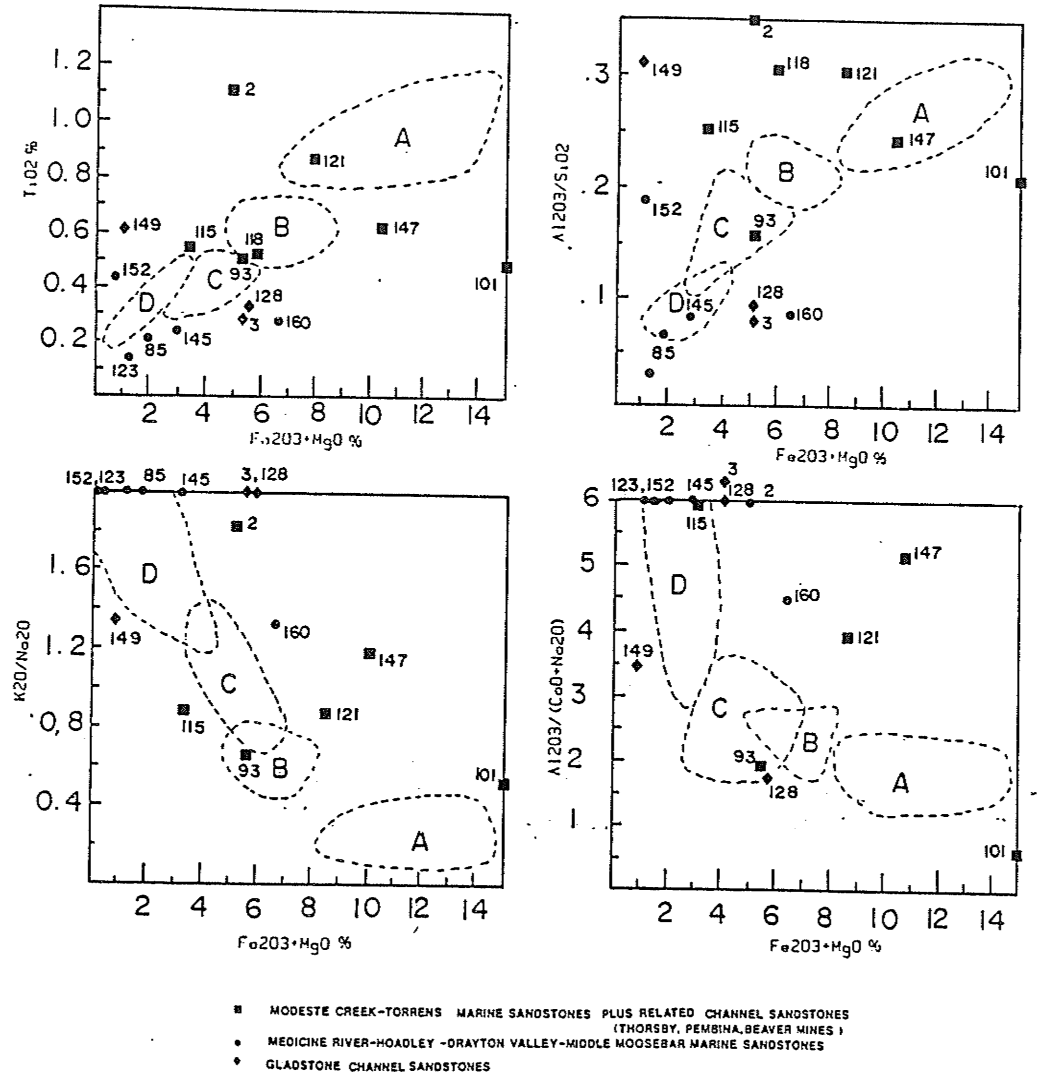
CHEMISTRY AND PROVENANCE

In the past decade, several studies (Bhatia 1983; Roser and Korsch 1986) have systematically investigated the relationship between the major element chemical composition of sandstones and the tectonic setting of the basin in which those sandstones were deposited. Both studies noted that sandstones are particularly difficult to classify and interpret on the basis of bulk chemistry alone as their characteristic high porosity and permeability permit them to behave as "open" geochemical systems during burial. Thus, during diagenesis, the bulk composition is subject to change, due to the addition of authigenic phases, or the dissolution or alteration of unstable framework or matrix material. Despite these problems however, the tectonic setting does appear to impart a characteristic signature which overwhelms the effects of post-diagenetic alteration, and can thus be used to interpret the provenance of sandstones of unknown parentage.

Bhatia (1983) introduced four binary plots which differentiated sandstones derived from various tectonic settings. To evaluate the provenance of the Lower Cretaceous sandstones, the weight percent oxide values were recalculated on a volatile-free basis and total iron was expressed as Fe_2O_3. The sandstones comprising each of the three chemical suites (described above) were plotted using different symbols (Fig. 48).

In general, the Early Cretaceous sandstones examined in this study exhibited a wide range in chemical composition and showed a much higher variablity than those plotted by Bhatia (1983). Approximately 20% of the samples from this study plotted off scale on these diagrams and samples from the same interval, and which contained similar petrographic (framework) composition, showed markedly different major element compositions. Despite this high variablity in composition, and poor correspondance with the tectonic fields designated by Bhatia (1983), several generalizations can be made concerning the provenance of the sandstones examined in this study.

Considerable overlap exists between the lower and middle sandstone suites on all of these plots (Fig. 48). These sandstones generally plot in, or near, the passive margin field which consists of "highly mature sandstone derived from the recycling of older sedimentary rocks" (Bhatia 1983). Although he does not differentiate a distinct field for foreland basin sandstones, this correspondance is to be expected as the foreland basin sandstones are typically recycled from older passive margin sequences (Dickinson and Suczek 1979).



A - OCEAN ISLAND ARC
B - ISLAND ARC ON CONTINENTAL CRUST
C - ACTIVE CONTINENTAL MARGIN
D - PASSIVE MARGIN

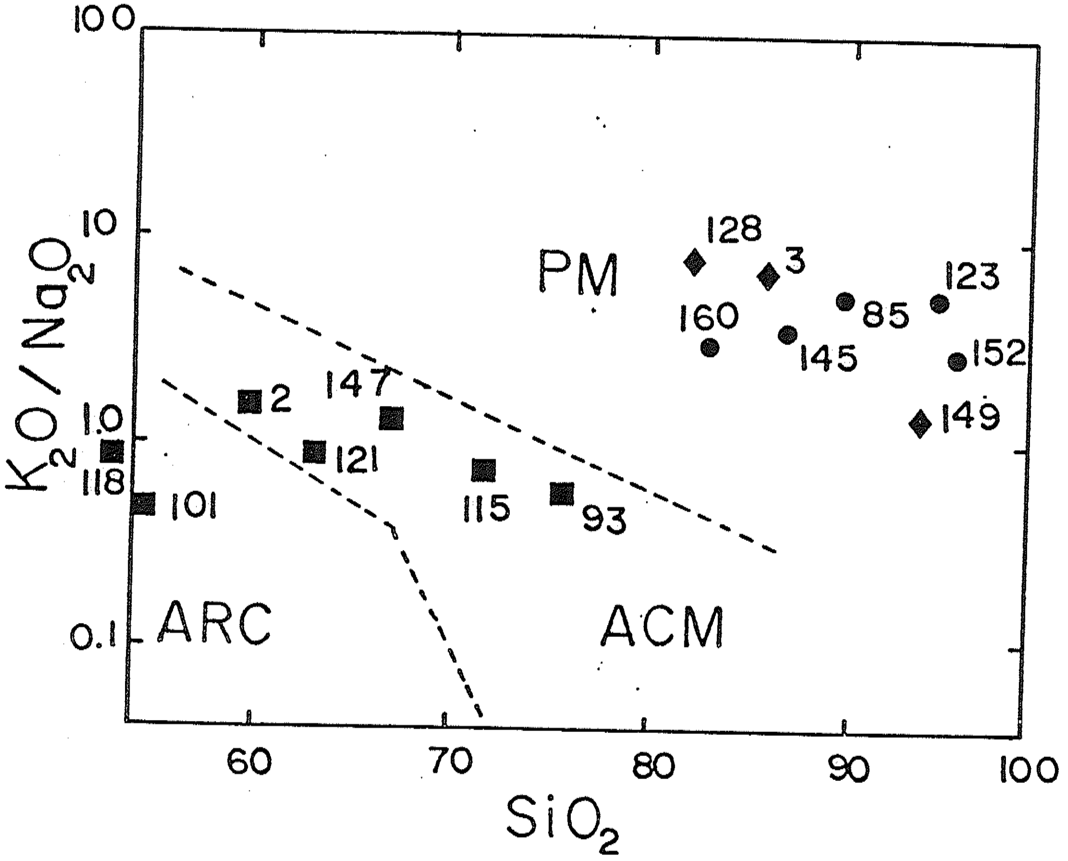
(48) Major element chemical composition of Blairmore-Mannville sandstone plotted on provenance diagrams proposed by Bhatia (1983).

Sandstones in the upper suite exhibit a wide range in composition and generally plot ouside of the fields outlined by Bhatia (1983). The higher Fe_2O_3 and MgO content of these sandstones, relative to sandstones from the lower and middle suites, forces these points to the right of all of the diagrams, towards the oceanic or continental island arc fields. While this is consistent with petrographic observations that these sandstones contain a significant volcanic component, the large range in their composition hinders more precise interpretation.

A second plot introduced by Roser and Korsch (1986) differentiates sandstones on the basis of SiO_2 versus K_2O/Na_2O values. These parameters were also calculated on a volatile-free basis and the sandstones comprising each of the three chemical suites (described above) were plotted using separate symbols (Fig. 49). This binary plot accommodates the data collected in this study much better than those proposed by Bhatia (1983) as only one of the samples (the pervasively carbonatized sample #118) plotted off scale on this diagram. Moreover, the data plots in two distinct fields, and this is consistent with petrographic observations that a dramatic change in provenance occurred in western Canada during the Early Cretaceous.

Samples from the lower and middle suite exhibit considerable overlap and fall within the passive margin field, as defined by Roser and Korsch (1986). Although they have not differentiated a foreland basin field on the diagram, this is where these samples should plot as the quartz and chert-rich foreland basin sandstone are typically derived from recycling of quartzose passive margin sequences (Dickinson and Suczek 1979).

Samples from the upper suite exhibit significantly lower SiO_2 and K_2O/Na_2O values and most plot within their active continental margin field. This field typically comprises quartz and feldspar-rich sandstones from continental margin



PM-- PASSIVE MARGIN
ACM - ACTIVE CONTINENTAL MARGIN
ARC - OCEANIC ISLAND ARC

■ MODESTE CREEK-TORRENS MARINE SANDSTONES PLUS RELATED CHANNEL SANDSTONES (THORSBY, PEMBINA, BEAVER MINES)
● MEDICINE RIVER-HOADLEY -DRAYTON VALLEY-MIDDLE MOOSEBAR MARINE SANDSTONES
◆ GLADSTONE CHANNEL SANDSTONES

(49) SiO2 values and K2O/Na2O ratios of Blairmore/Mannville sandstones plotted on provenance plots proposed by Roser and Korsch (1986).

arc-trench systems and strike-slip basins. The two samples of the upper suite which plot in or near the oceanic island arc field (#101, 118) both exhibit much more extensive carbonate replacement than the other samples and it is possible that diagenetic alteration has obscured the tectonic signature of these sandstones.

(e) SUMMARY OF PROVENANCE INTERPRETATIONS

Analysis of the petrography and major element chemistry of fifteen representative sandstone samples reveals that dramatic changes in the provenance of detritus occurred during the Early Cretaceous.

The Late Jurassic Rock Creek and Fernie and Early Cretaceous Cadomin-Gladstone-Ellerslie and basal Glauconite sandstones are quartz and/or chert-rich, contain virtually no feldspar or igneous and metamorphic rock fragments, and contain an ultra-stable heavy mineral assemblage. These sandstones were probably recycled from from older (Proterozoic, Paleozoic and Early Mesozoic) miogeoclinal clastic and carbonate sequences which were exposed in the foreland fold/thrust belt which flanked the western margin of the basin.

A major change in provenance occurred during the Early Albian as the Beaver Mines-Torrens sandstones in the Foothills, and equivalent sandstones in the upper Glauconite Formation in the subsurface, contain abundant (plagioclase) feldspar and volcanic rock fragments, in addition to the chert and quartz. These sandstones contain virtually no foliated quartz-mica (metamorphic) grains and contain a petrographic (framework) and chemical composition consistent with a continental magmatic arc, or strike-slip fault, tectonic setting.

The abundance of volcanically-derived detritus in the upper part of the Blairmore-Luscar has been noted by previous workers (Glaister 1959; Rapson

1965; Mellon 1967; Putnam and Pedskalny 1983) but the source of this material has never been clearly established. Since coeval (Jurassic-Early Cretaceous) volcanic sequences are not widely preserved in the southern Cordillera (Souther 1977), it appears that this detritus could only have been derived from one of two source terranes which include:

a) Late Paleozoic-Early Mesozoic (Triassic) volcanic piles in the allochthonous terranes in the Intermontane Belt.

b) a now-eroded volcanic arc system which was centered in the southern Omineca Crystalline Belt (Shushwap-Kootenay Arc area, Fig. 44). Although volcanic rocks of this age are not presently found in this area, numerous granitic plutons of this age (approximately 100Ma) have been described (Archibald et al. 1983) and these may represent the roots to a now largely eroded (dissected) magmatic arc. These plutons intrude, and therefore post-date an older metamorphic "core" complex which formed during during a Cretaceous collision of the North American craton and the allochthonous terranes (Archibald et al.1983). Mineral assemblages in this complex suggest that 13-17 km of cover has been stripped off since these granitic plutons were emplaced. This unroofing process could have stripped off the upper (extrusive) parts of the pile, such that only the plutonic roots are presently preserved.

The relative amounts of detritus contributed by these two volcanic source terranes could not be established using petrography. However, two indirect lines of evidence suggest that a magmatic arc in the southern Cordillera is a more likely candidate for the source of the volcanic detritus.

(1) It is unlikely that volcanic detritus from the allochthanous terranes in the Intermontane Belt could have traversed the elevated foreland fold/thrust belt to be deposited in the Alberta Basin. Dickinson and Suczek (1979) note that the fold/thrust belts typically shield the adjacent basin from receiving

sediment from the overiding plate.

2)Increased tectonic shortening and absence of large scale strike slip faults in the southern Cordillera have been cited as evidence that more extensive (oblique) subduction occurred in this area during the Early Cretaceous, relative to the northern Cordillera where most displacement was taken up along strike slip faults (Lambert and Chamberlin 1988). If significant subduction did occur in this area, then large amounts of magma must have been generated. The concentration of Early Cretaceous plutons in the Kootenay Arc, and the local development of Early Cretaceous extrusive rocks (Crownest Volcanics) are probably the only record of this magmatic event as most of the volcanic pile was apparently bevelled by erosion and redeposited in the adjacent basin.

Existing models of Cordilleran evolution (Monger et al. 1982; Lambert and Chamberlin 1988) do not explain why an abrupt change in sandstone provenance occurred during the Early Cretaceous. An alternative two-stage tectonic model, suggested here, invokes a shift in polarity of the subduction zone along the western margin of North America as the cause of this change in provenance.

During the initial stage, thrust sheets were piled up into a foreland fold/thrust belt as the the underriding (North American) plate was consumed along a west-dipping subduction zone which separated the allochthonous terranes from the craton, as described by Monger et al. (1982). These uplifted thrust sheets acted as source for the quartz and chert-rich lower Blairmore-Mannville sandstones in the adjacent Alberta Basin.

During the final stage, when the accretion of the allochthonous terranes with North America was essentially complete, subsequent convergence was taken up along an east-dipping subduction zone which developed along the western margin of the allochthonous blocks. During this stage, the North American craton, coupled with the newly accreted allochthonous terranes, formed the overriding plate and acted as a platform upon which a continental margin magmatic arc developed. This arc, which acted as the source of most of the volcanic detritus in the upper Blairmore and Mannville sandstones, is now largely eroded although the Early Cretaceous plutons in the southern Cordillera comprise the roots to this complex. A more detailed discussion of the tectonic evolution of the southern Cordillera will be presented in Chapter 11.